

REPORT NUMBER 161

JULY 1965

# **X353-5B AND X376 DESIGN SUMMARY REPORT**

**XV-5A**  
**LIFT FAN FLIGHT RESEARCH AIRCRAFT PROGRAM**

CONTRACT NUMBER DA44-177-TC-715

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X353-5B AND X376 DESIGN SUMMARY REPORT

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XY-5A LIFT FAN FLIGHT RESEARCH AIRCRAFT

Contract No. DA 44-177-TC-715

July 1965

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ADVANCED ENGINE AND TECHNOLOGY DEPARTMENT  
GENERAL ELECTRIC COMPANY  
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## I. SUMMARY

This report describes the work accomplished under the Propulsion and Pitch Fan Systems Sub-Program, Task I Design and Engineering of Contract DA 44-177-TC-715. Installation studies for compatibility of the X353-5B and X376 propulsion systems to the XV-5A aircraft are described as well as the aerodynamic mechanical design aspects of the lift fan system. Discussions will be centered around the changes to the fans developed beyond contract DA 44-177-TC-584.

## I I. I N S T A L L A T I O N

### A. MOUNTING

#### 1. X353-5B LIFT FAN

The mounting of the X353-5B lift fans in the aircraft is basically the same mounting used in developing the original X353-5 lift fans in the Evendale facility and the NASA Ames wind tunnel, but differs in two areas. In the original mounting arrangement, the three-directional master mount was located at the rear spar. However, once the airplane detailed design was started it became apparent it would be more compatible with the XV-5A wing design to locate the master mount at the front spar and would be lighter. Flightworthiness testing of the lift fan with the forward master mount showed there were no detrimental effects associated with this change.

A second mounting change was the addition of a tension link between the inboard fan mount and the "long leg" of the cross duct. This link spans the bellows between the long leg of the duct and the scroll horizontal inlet and absorbs most of the separating pressure load developed at this joint. However, the geometry of the remaining cross duct mounting links prevents this one tension link from being a lift fan mount in the true sense since it cannot absorb any other lift fan loads.

The lift fan mounting system is shown in Figure 1. The aft fan mount reacts to vertical and lateral fan loads while the inboard fan mount reacts to vertical and axial loads. The scroll torque load is transmitted

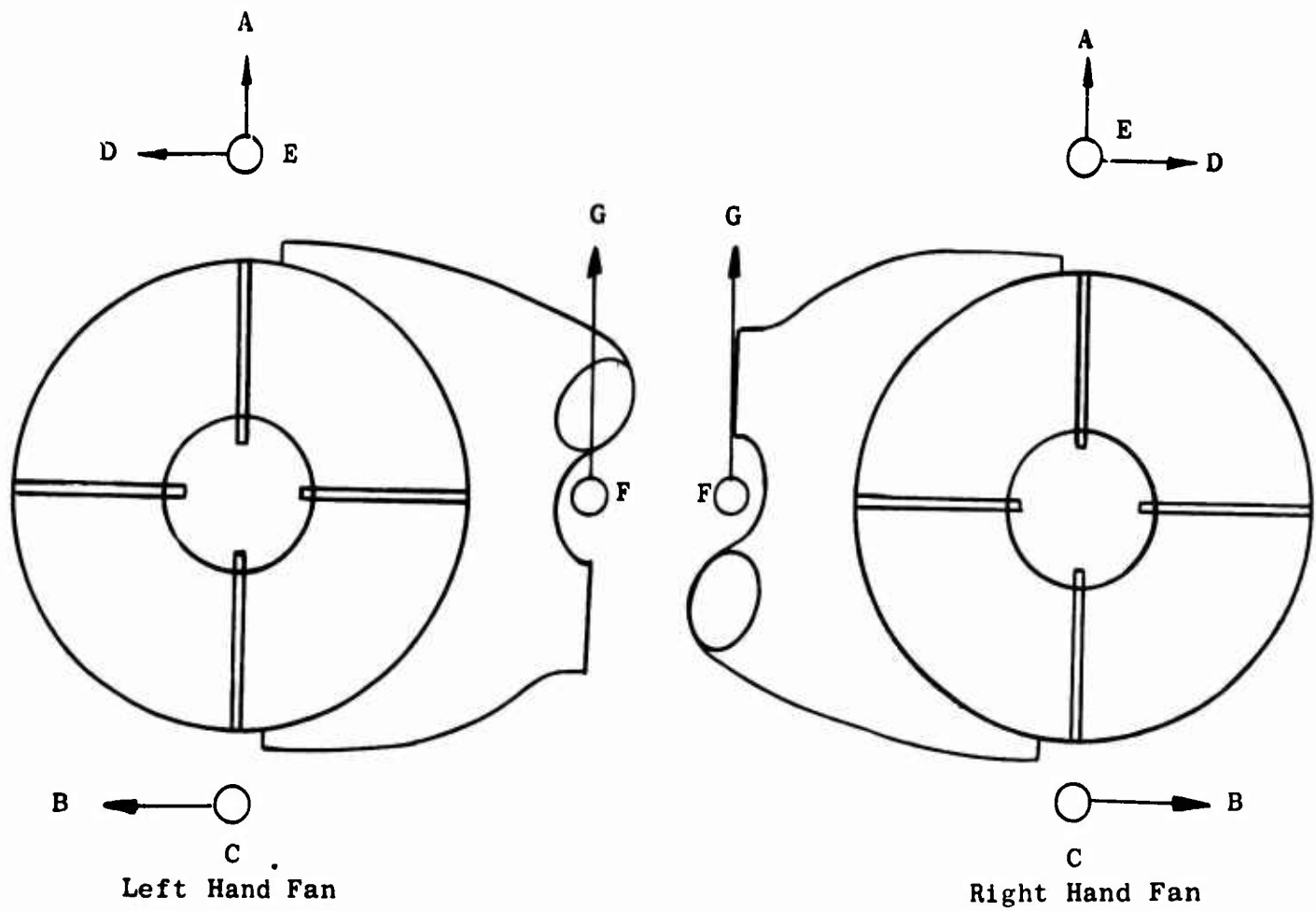


Figure 1. Lift Fan Mounting System

through the axial link into the wing spar and to the fan spar mount instead of through the fan front frame in order to conserve frame weight.

## 2. X376 PITCH FAN

The X376 pitch fan mounting system was designed to obtain the smallest possible pitch fan weight consistent with feasible attachment points in the airframe. The master mount, reacting to vertical, lateral and axial loads, is located aft of the pitch fan (6 o'clock position). A second mount, on the right hand side (3 o'clock) at butt line 59.0, reacts to axial and vertical loads while the left hand side mount (9 o'clock), also at butt line 59.0, reacts to vertical loads only (Figure 2).

## 3. J85 AND DIVERTER VALVE

The J85 and diverter valve are mounted as an integral unit. The major mounts on each side of the diverter valve body transmit turbojet thrust and also bellows pressure loads in the VTOL mode, and are located to minimize bending in the engine casings. A lateral stabilizing link is located at the diverter valve forward flange on the bottom whereas the forward vertical restraint at the rear compressor flange, is identical with other J85 installations (Figure 3).

## 4. CROSS DUCT

Considerable design effort was expended on cross duct mounting and bellows configuration, since these components would have to absorb the thermal growth between the engine and fan mounts. The geometry of the cross ducts, dictated by the relative positions of the engines and lift fans, produced a difficult bellows and mount design since it was highly desirable to have only axial bellows deflections from a convolution stress standpoint. However, it was apparent that this objective could not be

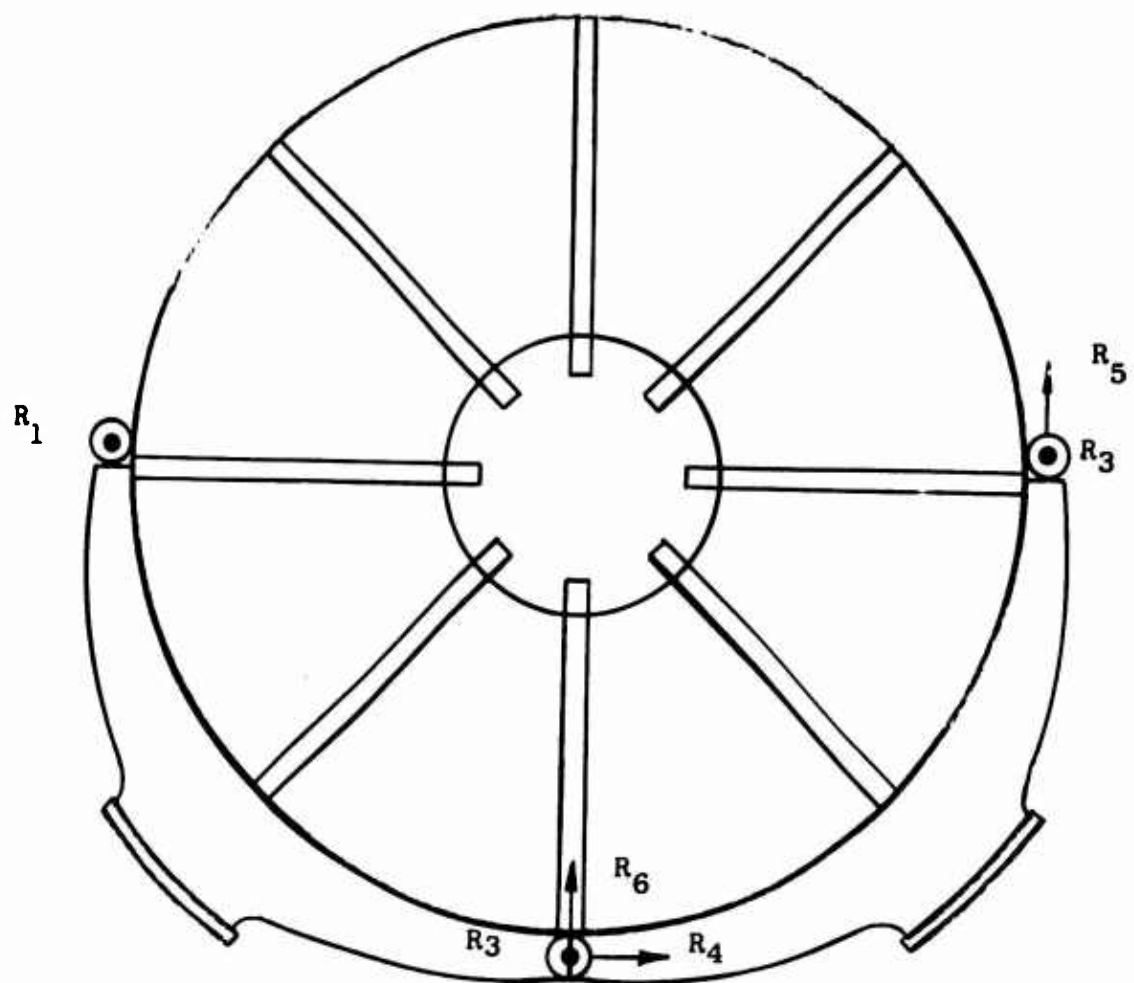


Figure 2. Pitch Fan Mounting System

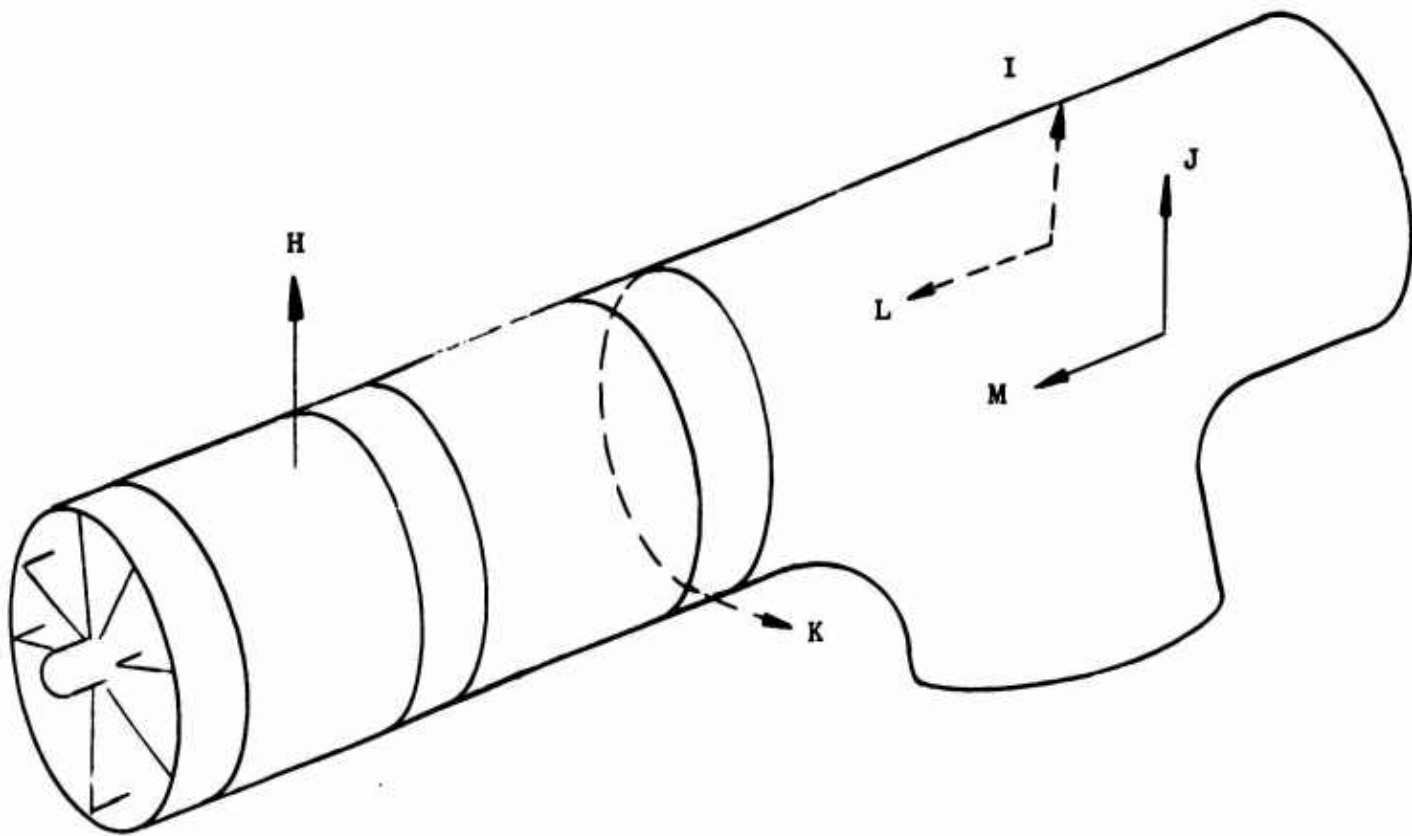


Figure 3. J85, Diverter Valve Mounting System

fully attained and that a finite amount of lateral, shear deflection would be required. The final mounting system was arrived at with two points in mind: (1) maintaining bellows shear deflections as small as possible and, (2) producing a mounting arrangement that was compatible with the construction of the fuselage space frame. The final mounting system, a conventional 3-2-1 arrangement, is shown on Figure 4 and was arrived at as a joint effort between General Electric and Ryan engineering.

During this design effort, considerable attention was given to the use of ball and slip joints as substitutes for the bellows, since the lateral as well as axial deflections were large. However, hot gas leakage through these joints, estimated at  $\frac{1}{2}\%$  of cross duct flow based on the current state-of-the-art, would have imposed a very heavy heating load on the airframe cooling system and ball and slip joints were rejected on this basis. All cross duct bellows, originally conceived as single skin convolutions, are used as two-ply convolutions which give considerably more lateral flexibility. Exhaustive testing has shown no failures through 242 hours of engine and fan operation.

#### B. COOLING

The primary problem in cooling the powerplants and airframe in the XV-5A occurs during fan supported flight where there is no ram pressure available, nor any tailpipe ejector action.

The need for an engine-driven cooling blower was indicated early in the program. Initially it was intended that this blower would only serve the two J85 engines. The space around the lift fans in the wing and the cross ducts in the fuselage were to be purged by blowers submerged in the wing outboard of the fans, which would force air around the fan and towards the fuselage. Openings in the fuselage wall above the fan would allow the cooling air to exhaust into the low pressure field in this area.

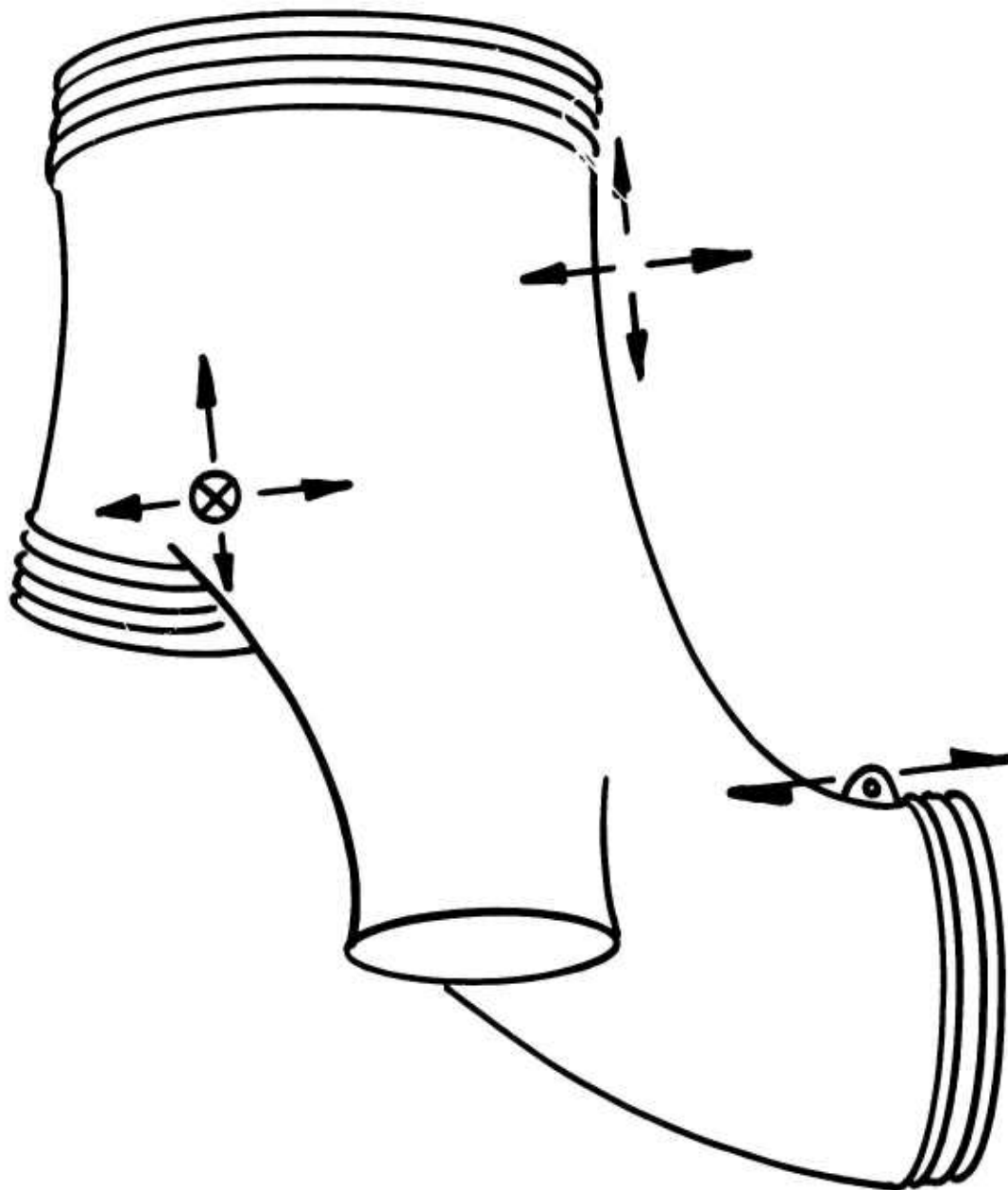


Figure 4. XV-5A Cross Duct Mounting



Tests were made on the 26 inch scale model fan to establish the static pressure distribution on the fuselage wall above the lift fan (Figure 5) and showed a relatively weak suction pressure in this area. In an effort to utilize the suction pressure of the fan more effectively, slots were placed in the strut fairing which extends fore and aft over the fan major strut. Being closer to the rotor, the flow velocities are considerably higher and more cooling air could be drawn through the system. A branch duct was added to the J85 driven blower to supply this air (through the cross duct compartment) and the wing-mounted blower was eliminated, making the total system considerably lighter.

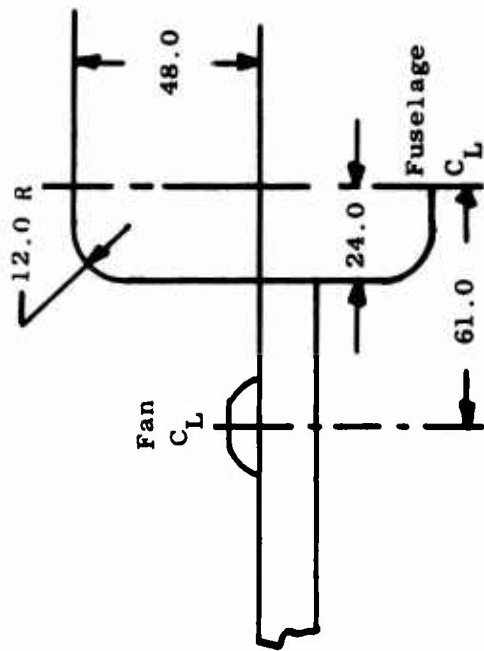
The pitch fan ducts and scrolls were originally to be cooled by an external air scoop, drawing air into the forward fuselage and exhausting it into the pitch fan inlet immediately above the pitch fan rotor. However, temperature data, obtained at NASA Ames on the XV-5A model, showed that there was no practical location for an external scoop that would assure a supply of cool air under all conditions of fan supported flight. As a result, the J85 driven blowers, with inlets well out of the reingestion area, were required to supply this air.

### C. FAN INLETS AND CLOSURES

#### 1. MAIN FAN INLET DOORS

The design objectives for the main fan inlet closure system were to achieve satisfactory fan aerodynamic and mechanical performance while producing the least possible airplane drag. Analysis and test work was focused principally on a butterfly door concept, hinged along the fan major strut and opening back-to-back, Figure 6. Both a faired door (streamlined over the bullethead) and an unfaired (protruding bullethead) door version were evaluated to reach the most favorable design.

SLS Hover - 100% N  
(Based on 26" Model Fan Tests)



- Fuselage Station 256.0
- △ Fuselage Station 246.4 and 265.6
- Fuselage Station 236.8 and 275.2
- ◇ Fuselage Station 225.4 and 286.6

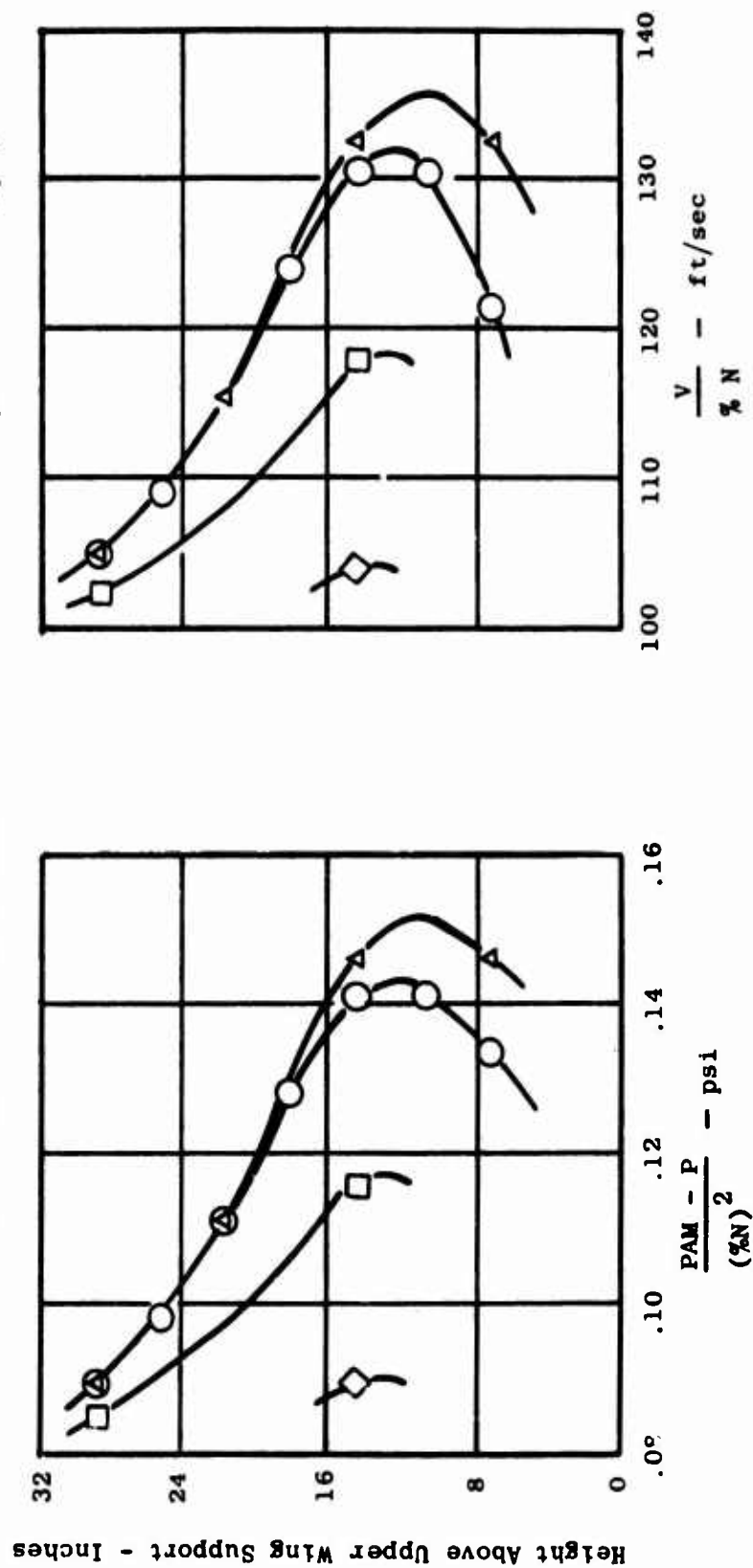


Figure 5. Pressure & Velocity Distribution

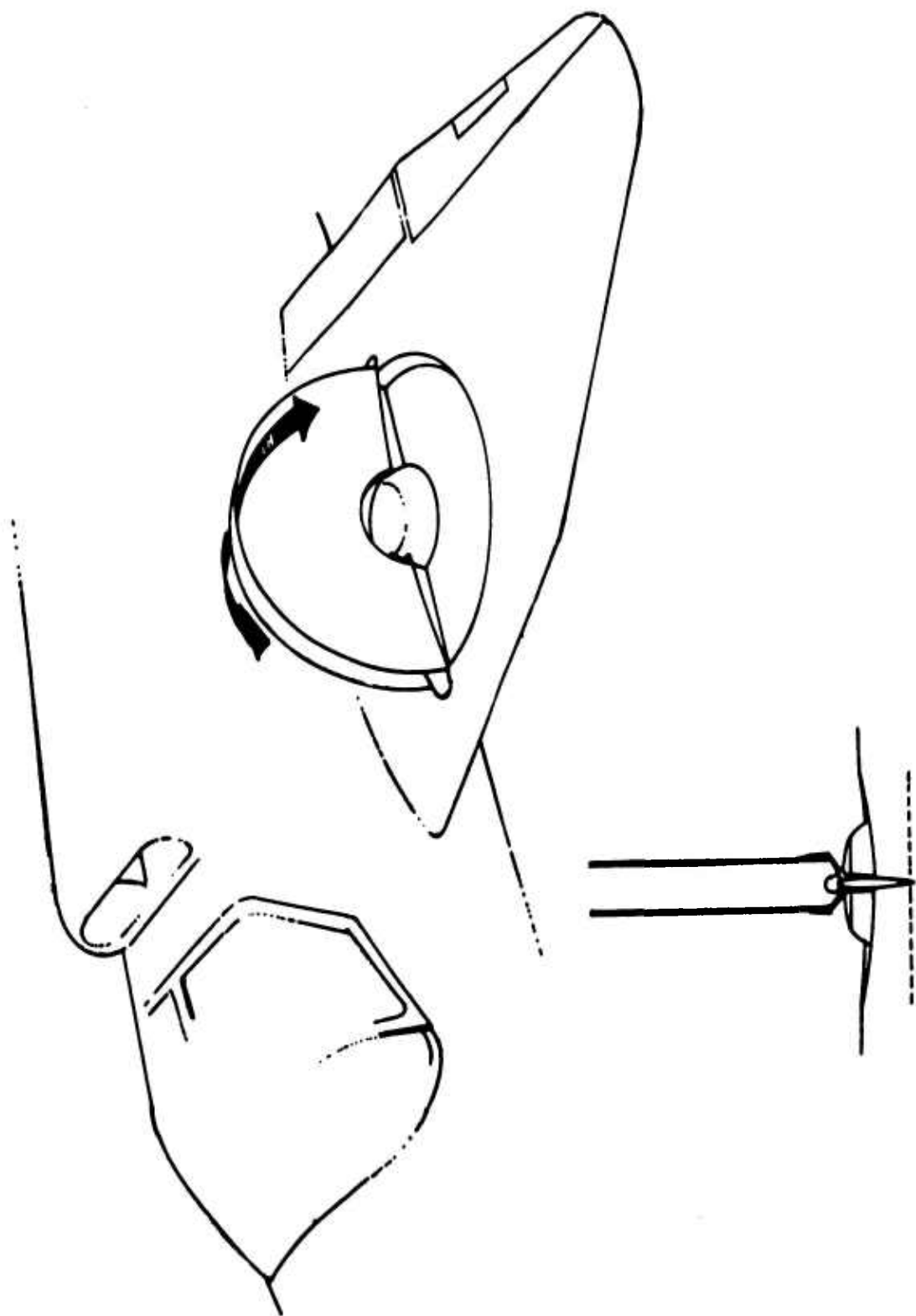


Figure 6. Unjoined Butterfly Doors

Preliminary experimental evaluation of the effects of door closures was obtained using the Ames full scale fan-in-wing model and with both faired and unfaired door systems. Performance of the fan was unaffected by either of the door systems tested with the model out of ground effect; however, a  $1\frac{1}{2}$  to 2% lift loss was indicated with the faired door system at ground heights of one fan diameter. Additional evaluations were made either with the faired door closure system using the 26 inch scale model fan facility at Evendale, Ohio. Test results for the scale model system in the NASA Ames configuration were in reasonable agreement with the previous full scale Ames results. Various door positions and shapes were examined, with the final scale model tests indicating the faired door system gave minimum (less than  $1\frac{1}{2}$ %) lift loss, providing the fairing radius of curvature is as large as possible.

Both door systems were evaluated by the airframe subcontractor. The effects of the protruding bullethead as it exists in the unfaired door system would probably produce, during conventional flight, unacceptable buffeting and critical drag beside the numerous sealing and actuation problems that are alleviated by the faired door system. Based upon the 26 inch scale model tests, Ames tests, and mechanical design aspects, the faired door system was selected for the XV-5A airplane and carried through the detailed mechanical design.

## 2. PITCH FAN INLET CLOSURE AND REVERSER

### Summary

The design and development of the pitch control fan inlet and closure was centered around a low speed scale model experimental program. The inlet was first investigated in an axisymmetric installation and then in a three-dimensional model conforming to the fuselage shape. Closure devices were tested and developed in this model under static conditions and conditions simulating forward flight.

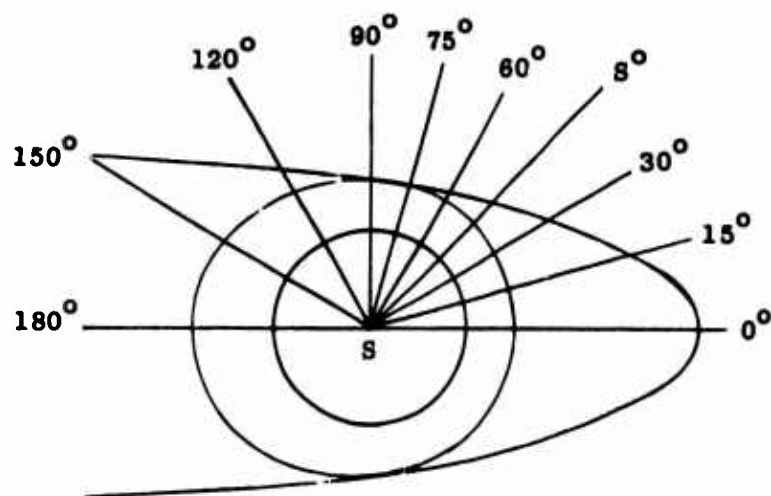
The reverser was first investigated as a two-dimensional model representation of the lower portion of the fuselage at the fan center line. After a number of aspects were investigated in this two-dimensional model which permitted rapid design changes, a three-dimensional model representative of the final fuselage shape was tested. Adequate inlet operation, closure, and thrust reversal were demonstrated before design release. Features to obtain thrust reversal in excess of requirements were identified and tested.

### Inlet

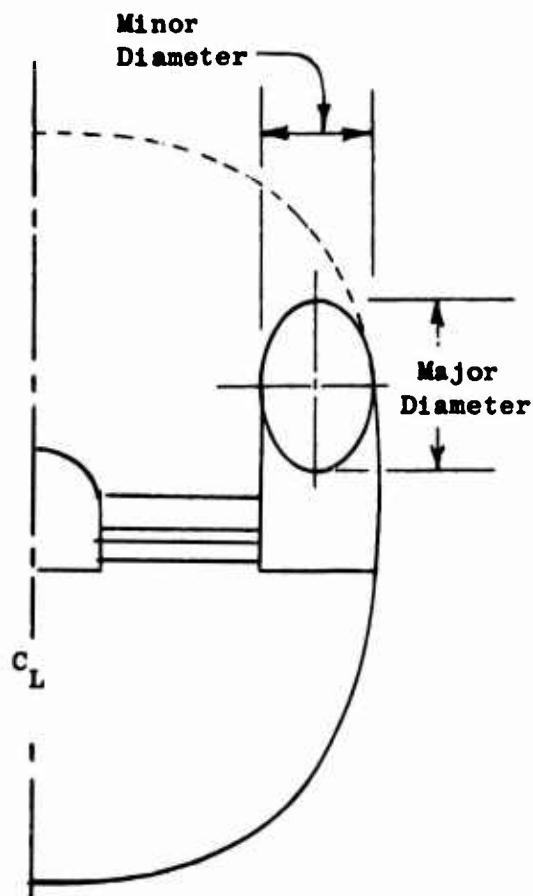
The inlet conforms to the fuselage surface in the vicinity of the fan. To permit the maximum amount of space below the fan for reverser mechanisms, the fan is located as high in the fuselage as possible, limited by the minimum bellmouth radius which occurs at the sides.

The bellmouth fairs to the fuselage with elliptical sections which previous tests showed to be superior to circular sections. The tightest turn occurs 75 degrees on either side from the forward direction. Figure 7 which depicts the elliptical section, lists the ratio of minor half-diameter to fan diameter (akin to bellmouth radius to fan inlet diameter for circular bellmouths), and the ratio of the minor to major diameter, versus angular location around the fan measured from the forward direction.

Two types of inlet closures were evaluated, both at static condition and conditions simulating forward flight. These are shown schematically in Figures 8 and 9. The longitudinal louver system was selected based upon mechanical design aspects such as weight and simplicity coupled with the fact that no aerodynamic performance difference could be determined. Further testing evaluated the effect of a yoke strut of considerable thickness to support the louvers (Figure 10), determination of orientation angles for the louvers in the open position, and wall static pressures throughout the inlet as required for designing purge air ports.



Typical Section S-S



Location	0°	15°	30°	60°	75°	90°	120°	150°	180°
Minor Diameter/Fan Diameter	.137	.137	.128	.086	.076	.088	.150	.150	.150
Minor Diameter/Major Diameter	.866	.866	.866	.707	.707	.707	.866	.866	.866

Figure 7. Pitch Fan Inlet Cross-Section

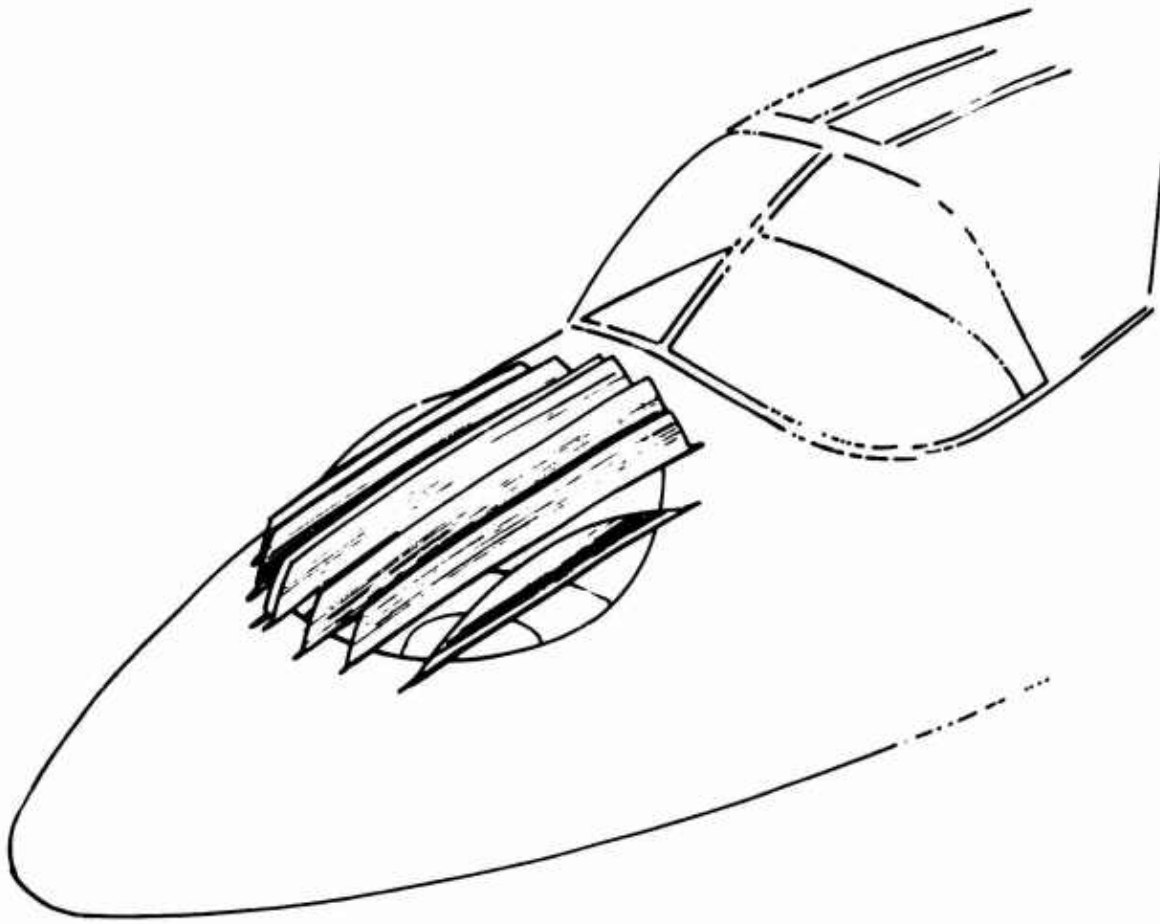
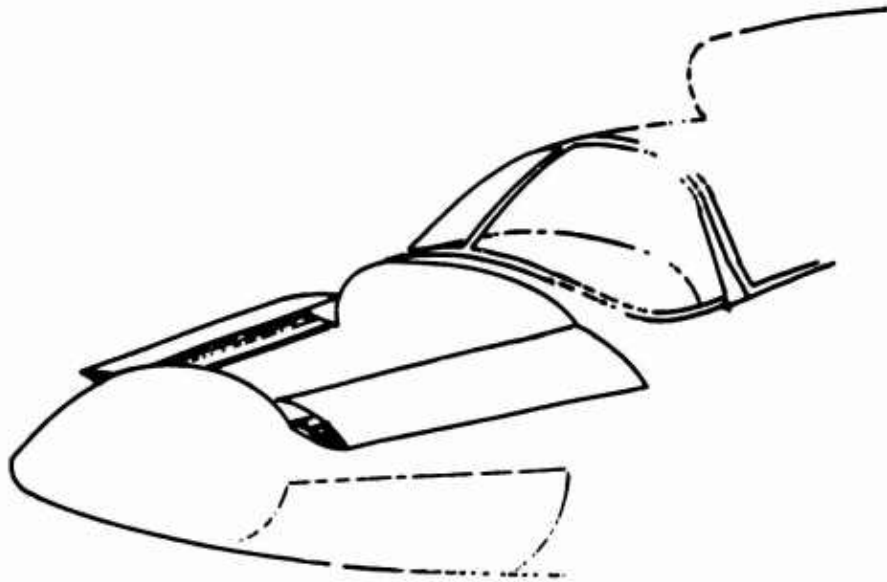


Figure 8. Pitch Fan Closure, Longitudinal Louvers



**Figure 9. Pitch Fan Closure, Folding Side Doors**



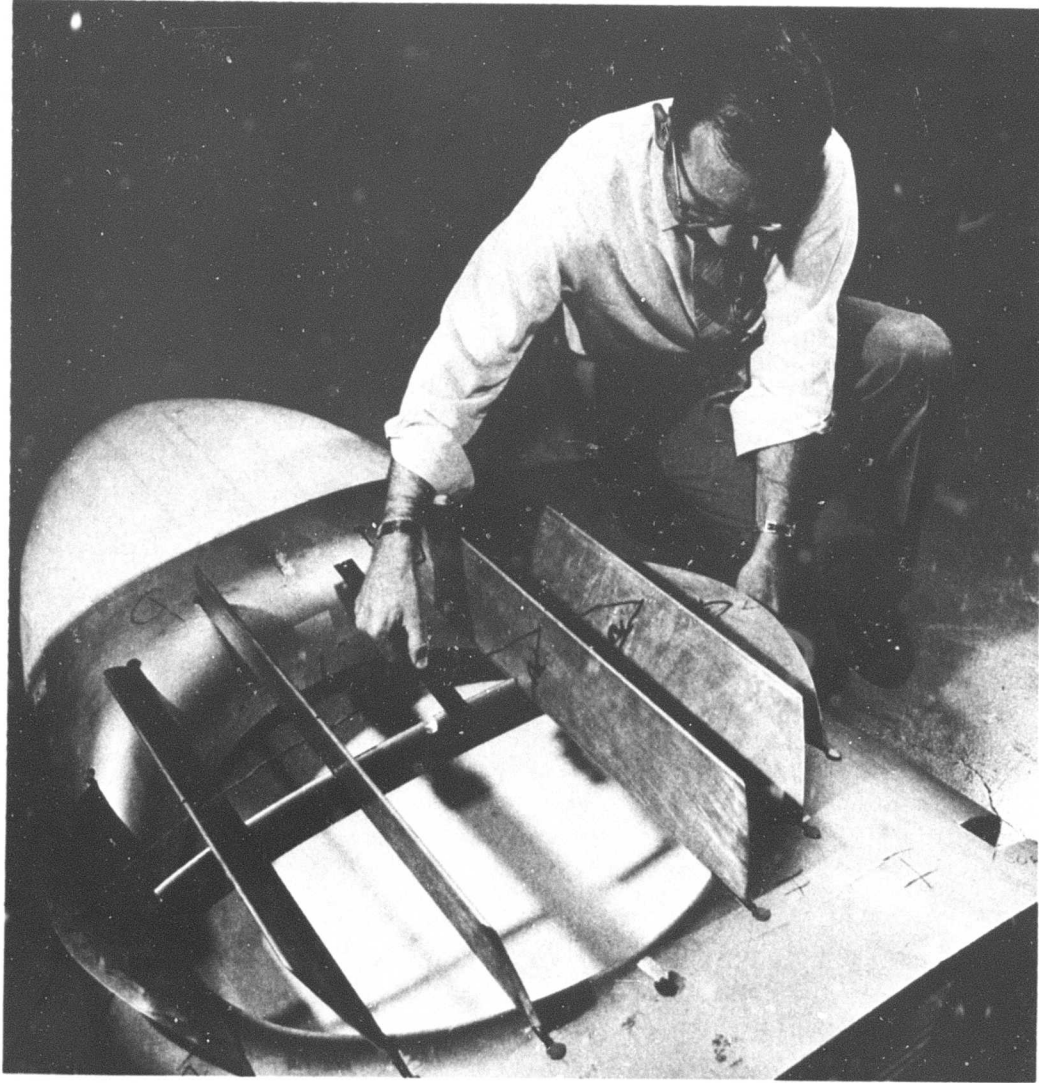


Figure 10. Maximum Thickness Transverse Strut

Separation occurs at the forward portion of the inlet under conditions of forward flight. A bellmouth vane was designed for the inlet and test hardware was manufactured for possible use during the Ames wind tunnel tests. Test results at NASA Ames, both aerodynamic and mechanical (from a rotor stress viewpoint), did not indicate need for this pitch fan inlet vane.

### Thrust Reverser Design

The pitch fan exit-reverser system was selected from five conceptual designs and tested in the 26 inch low speed scale model test facility. Initially the configuration was two-dimensional to facilitate variation of test variables. As shown in Figure 11, the test reverser consisted of a pair of thin doors which, in their closed position, form the lower fuselage contour. For maximum lift operation the doors are positioned as shown in Figure 11. For thrust reversal, the doors are rotated from the maximum lift position toward the closed position. The maximum reverse thrust position is shown in Figure 12. A series of static and cross-flow tests were run during which the test variables included: (1) door angle, (2) location of door pivot point, (3) door shape and length, (4) fences at the door ends, and (5) "trip strips" on the outer surface running fore and aft.

A three-dimensional inlet and reverser was constructed and tested to further evaluate the test variables listed above. Performance measurements of the final configuration are shown on Figure 13.

During Flightworthiness Rating Tests, a full scale test thrust reverser was utilized to determine full scale performance as well as possible pitch fan effects. As the aircraft program developed, a need for additional reverse thrust was postulated during wind tunnel testing by NASA Ames. A centerline strut and auxiliary turning vane (Figure 14)

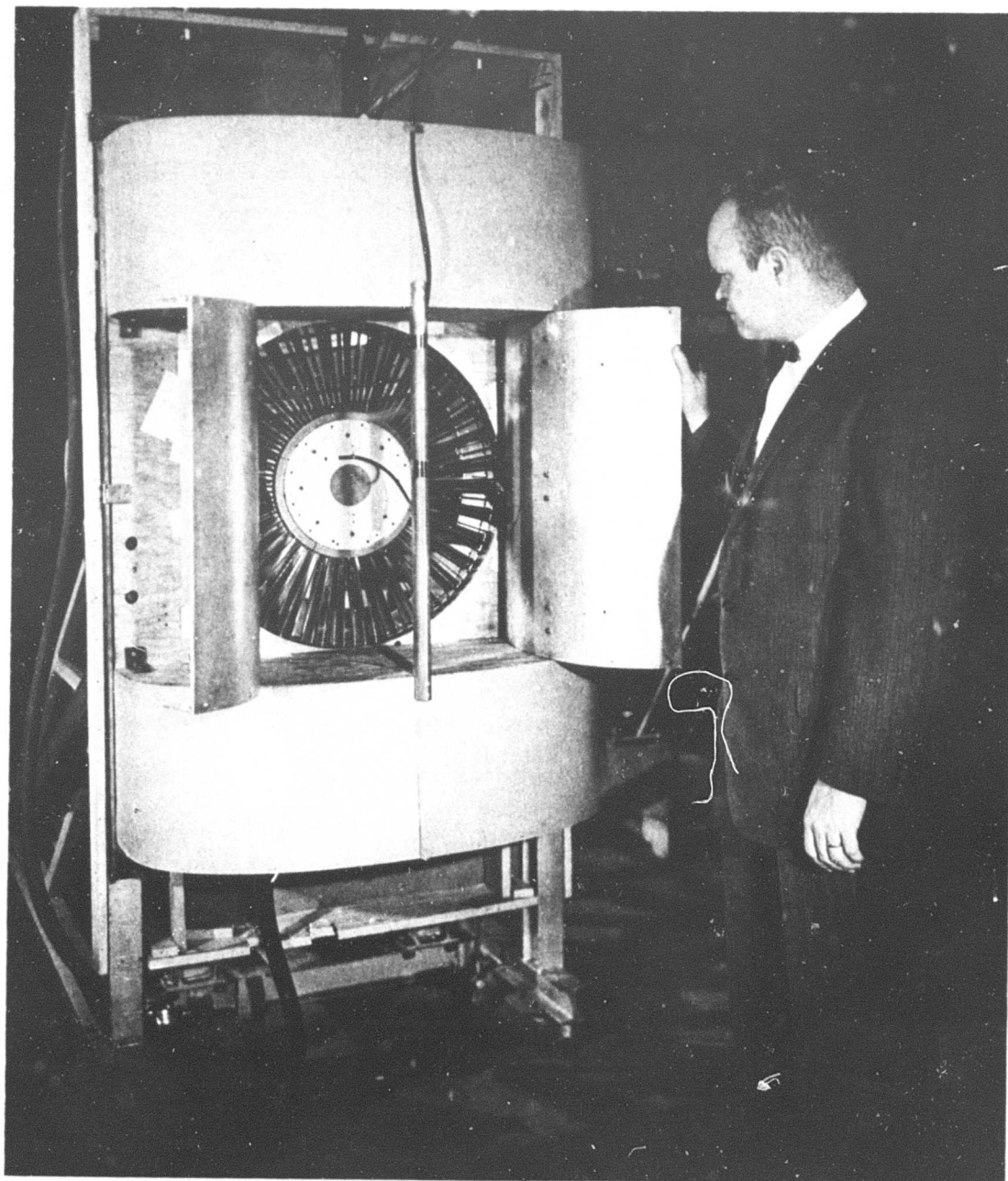


Figure 11. Test Flow Modulator, Open Position

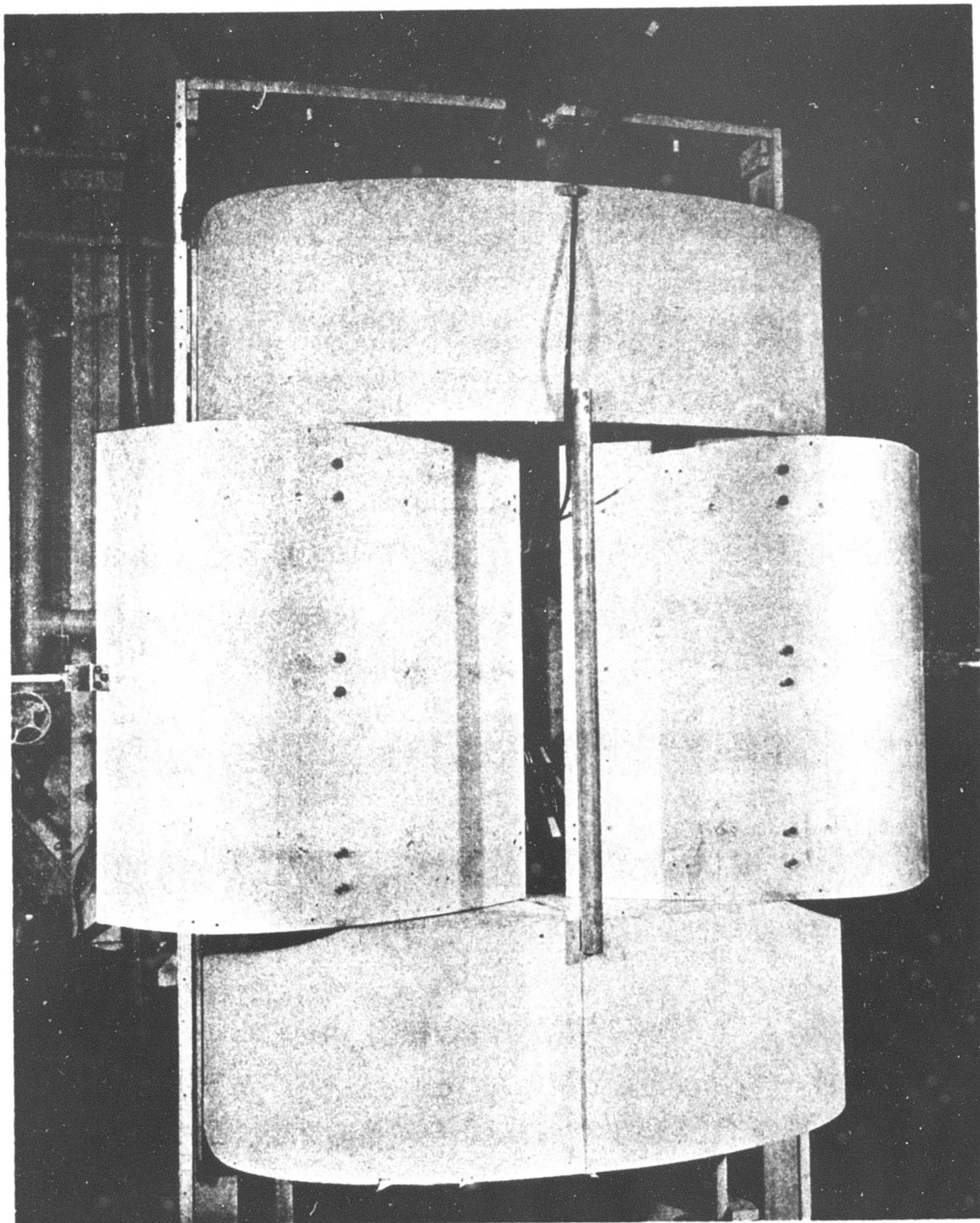


Figure 12. Test Flow Modulator, Closed Position

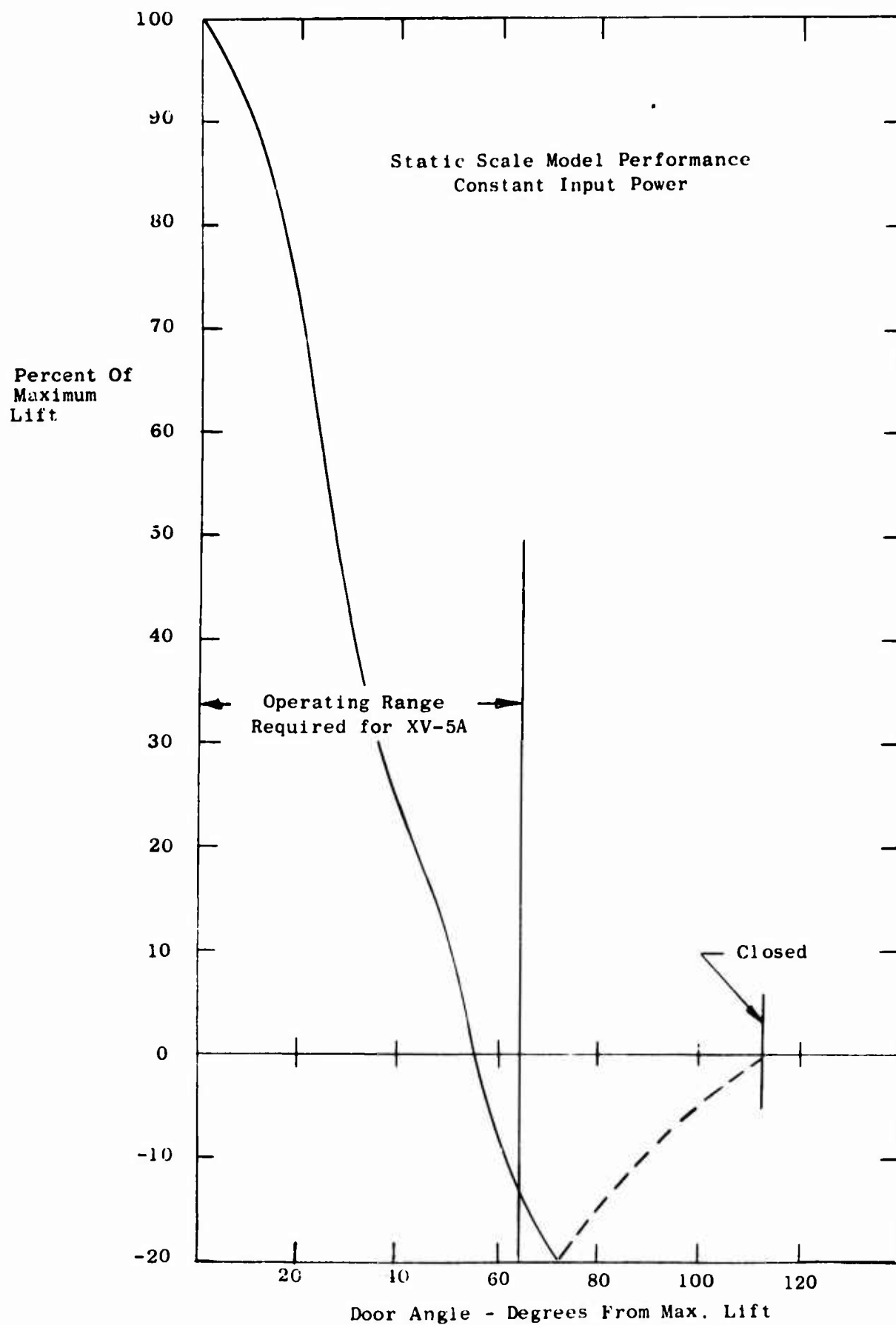


Figure 13. Fan Thrust Versus Door Angle

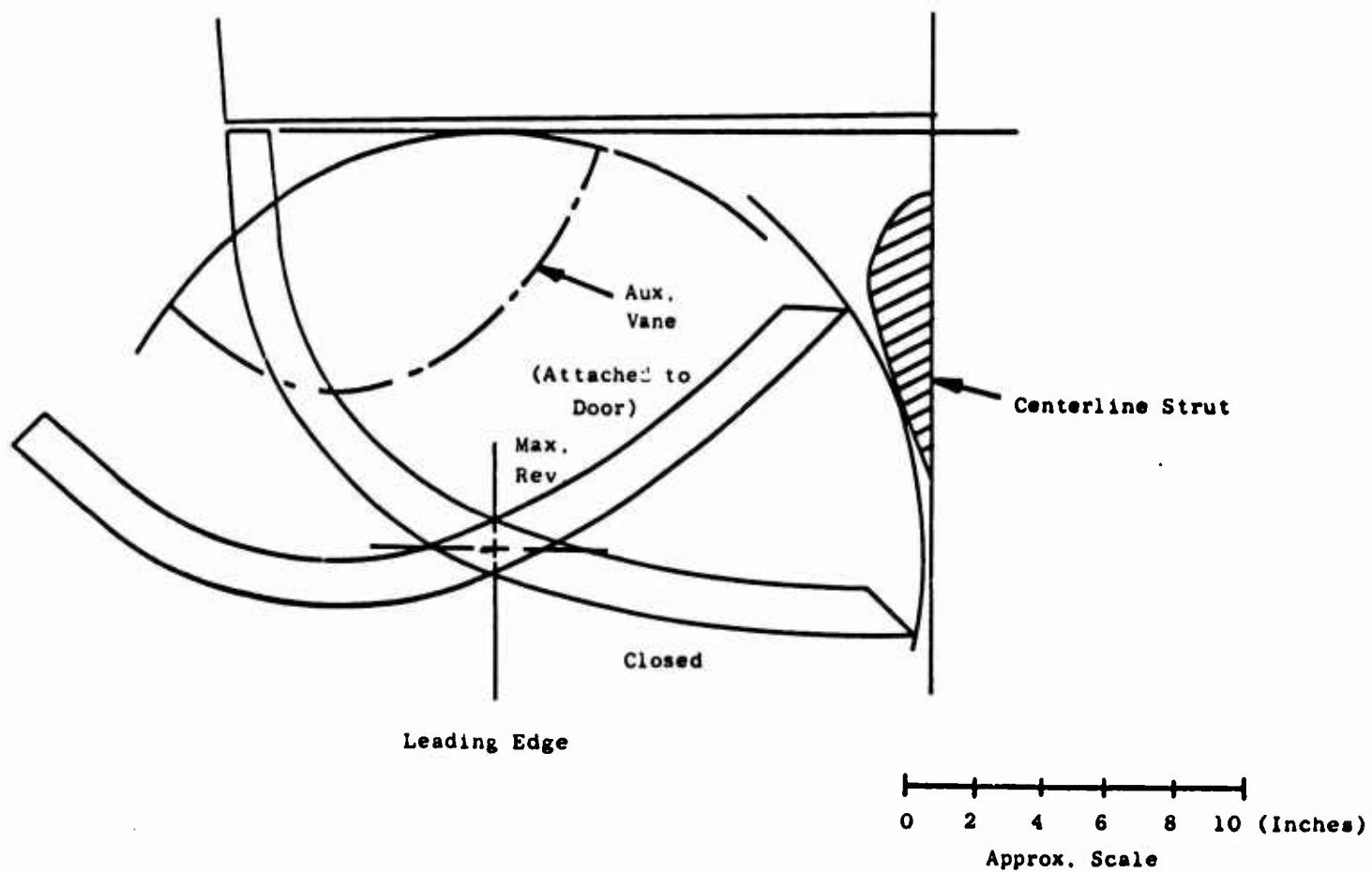


Figure 14. Sketch of System for Increasing Reverse Thrust Capability of Pitch Fan

were designed and tested during full scale pitch fan tests at Evendale. Based upon the test results shown in Figure 15, where a reverse thrust capability of greater than 35% was achieved as compared to 19% for the original design, this modified design was incorporated into both research aircraft.

#### D. DUCTING AERODYNAMICS

Aerodynamic tests were conducted on scale models of the diverter valve, cross duct, and left hand scroll inlet. The 5/8th scale model size provided a convenient test size and also permitted simulation of full scale Mach numbers and Reynold's numbers.

The initial cross duct configuration was modified through joint efforts of the contractor and the aircraft subcontractor to provide smoother flow paths, more gradual turns, and interchangeability between right and left hand cross duct assemblies. From this design effort, a scale model of the cross duct, shown in Figure 16, was built and tested in conjunction with other elements of the flow path.

Tests were conducted at Evendale by drawing ambient room air through the models by creating a vacuum at the model discharge. Flow orifices were used in the ducting downstream of the other branches of the cross duct to maintain correct flow separation. Through the use of total and static pressure and air flow measurements taken throughout the system, component and system losses were determined.

Table I presents test results in pressure loss coefficients for the various test conditions, while Table II defines the flow split between the various cross duct legs. The pressure loss coefficients for the combined diffuser, diverter valve, and for the cross duct alone are based on the dynamic head at the bellmouth. The scroll pressure loss coefficients are based on the average dynamic head at the scroll inlet flange. Since scroll

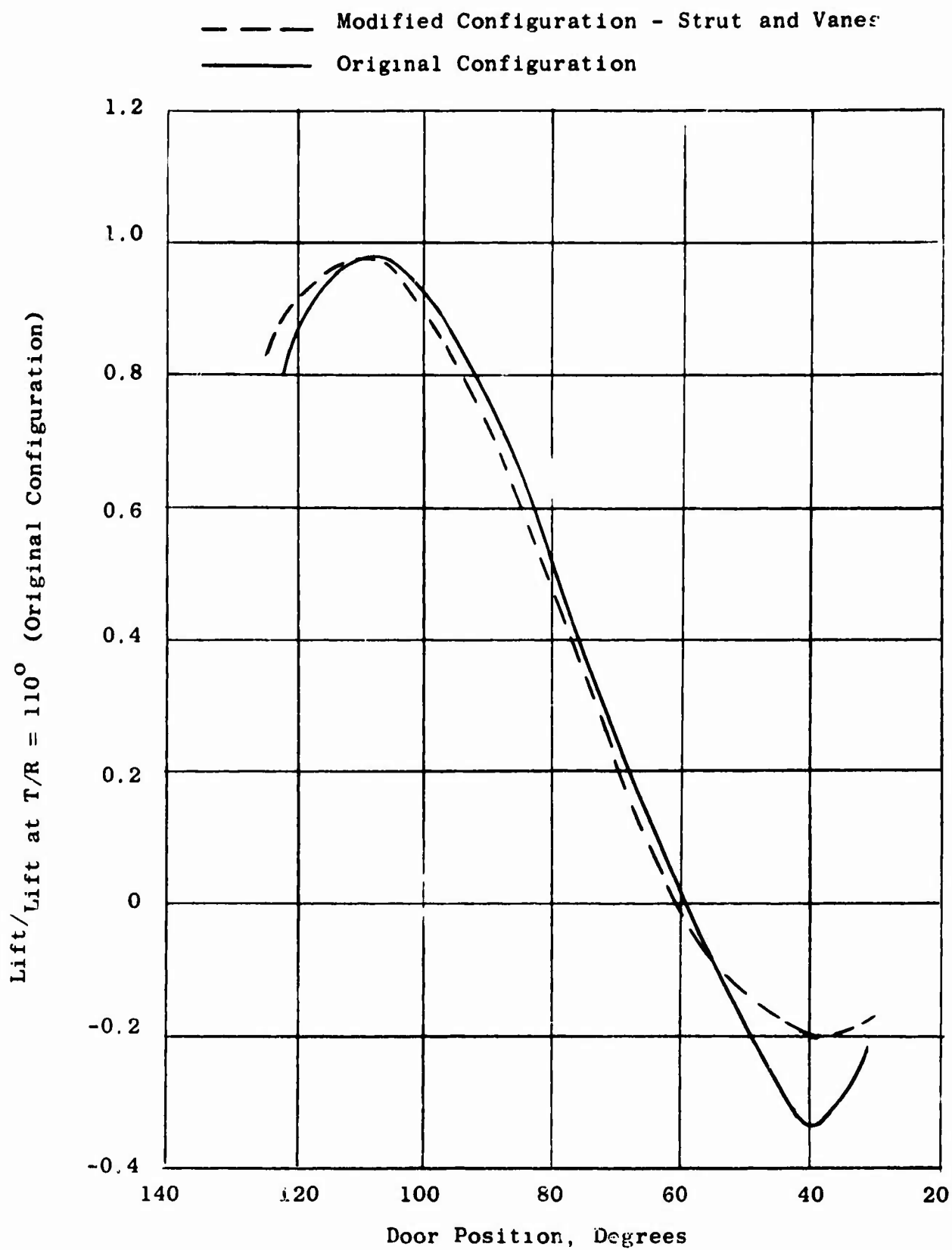


Figure 15. Comparison of Lift Variation - Pitch Fan  
 (Original Versus Combination of Strut & Vanes)



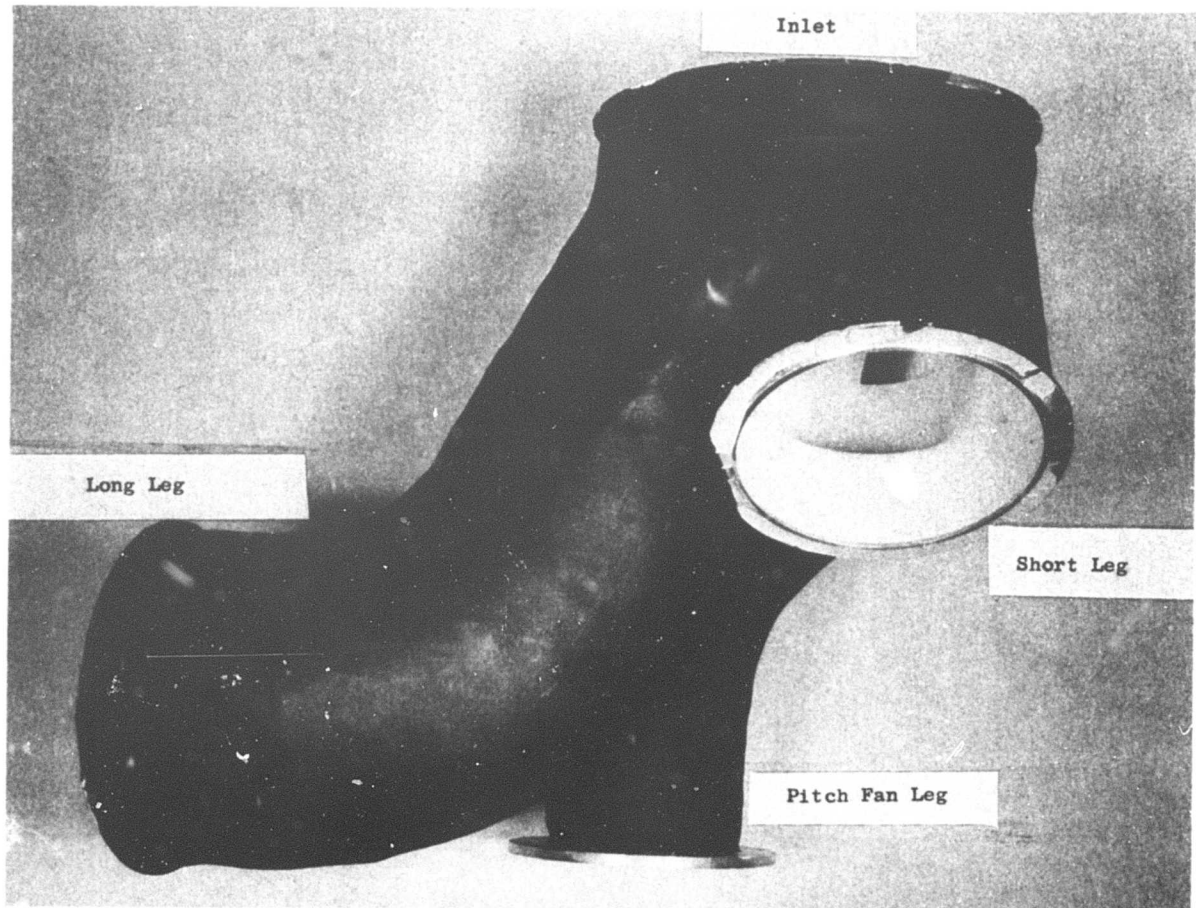


Figure 16. Scale Model Cross Duct

TABLE I

Pressure Loss Coefficients

Test Condition	1	2	3	4	5	6
<u>Diff., Div. Valve &amp; Cross Duct:</u>						
Average	.878	.864				
Short leg	.704	.700				
Pitch fan leg	.896	.891				
Long leg	1.047	1.021				
<u>Cross Duct Alone:</u>						
Average			.254	.223	.182	
Short leg			.124	.117	.087	
Pitch fan leg			.196	.184	.160	
Long leg			.396	.338	.282	
<u>Scroll:</u>	.481	.544	.371		.389	.532

Test Condition

1. Complete system tested - no scroll struts
  2. Complete system tested - scroll struts added
  3. Cross-duct and scroll tested alone
  4. Cross-duct and scroll tested alone
  5. Cross-duct and scroll tested alone
  6. Scroll tested alone
- } — varied cross-duct  
flow split

TABLE II

Cross-Duct Flow Splits

Test Condition	1 2 & 3	4	5
Long Leg Flow, %	46	44	39
Short Leg Flow, %	44	47	53
Pitch Fan Leg Flow, %	10	9	8

nozzle losses were determined during previous scroll tests, these losses have been subtracted from the measured overall scroll and nozzle loss.

A comparison of the test results for conditions 1 and 2 indicate that the scroll loss increased slightly with the addition of the struts. This loss increment is slightly larger than for the original X353-5 single entry scroll, however, this loss is relatively small. Loss coefficients for the diffuser-diverter valve-cross duct combination have remained unchanged from the X353-5 design.

Test conditions 3 through 5 indicate that as the flow in the cross duct short leg is increased, the loss coefficient of all legs decreases slightly. This could be due to a flow improvement at the entrance region of the short duct. however, observation of tufts within the cross duct did not indicate flow separation points for any of the test conditions.

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### I I I.    D E S I G N

#### A.    X353-5B LIFT FAN

##### 1.    FRONT FRAME

###### a.    Basic Frame

Several design changes were necessary to the X353-5 front frame to make it suitable for the XV-5A airplane. These changes consist of adding a fourth strut, provisions for a new inlet closure and actuation mechanism, removal of the inlet louver bushing, an integral support beam, and provision for a new inlet vane assembly.

The new fourth stru', Figure 17, was added to the frame at the 9:00 o'clock position between the hub and bellmouth. Its purpose was to force the "cold sector" of the frame to follow the rotor tip axial displacement during steady state and maneuver conditions, as well as to maintain the frame roundness during the manufacturing cycle. Analytical studies identified the additional strut as preferable over an axial 9:00 o'clock restraining mount. The addition of a 9:00 o'clock mount created an unacceptable redundant restraint and caused wing deflections to be absorbed by the fan frame. The new strut, which has the same constant cross section as the existing minor strut, has the advantage of permitting a symmetrical mounting system for the inlet vanes, thus eliminating the need for left and right hand assemblies. The new strut also allowed a closure latching system to be installed on the fan "cold side" to hold the fan inlet doors closed during conventional flight.

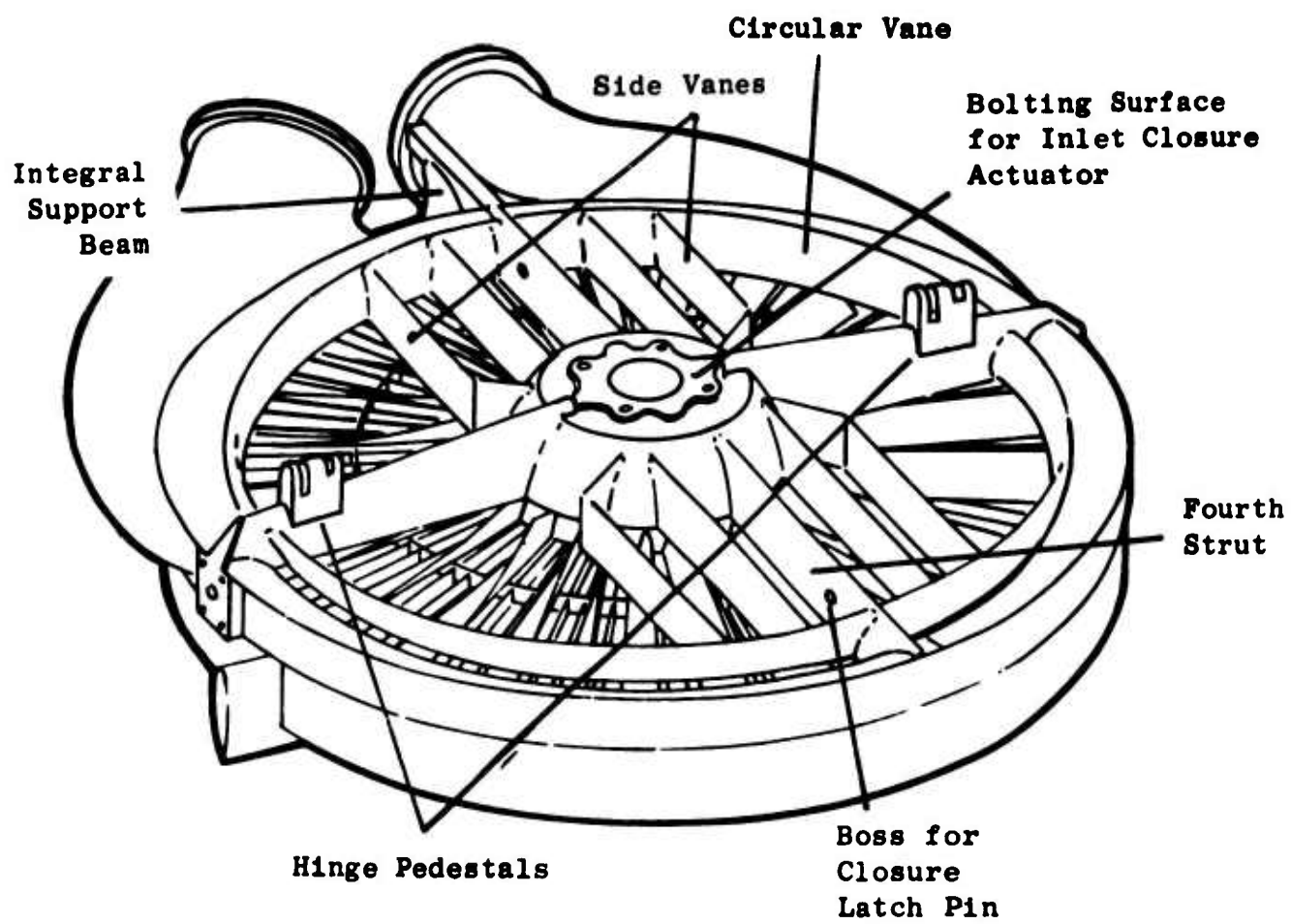


Figure 17. Front Frame Configuration

To allow provision for mounting the "butterfly" inlet closures and actuation mechanism it was necessary to redesign the main mounting strut and central hub. Each closure door required the addition of four hinge points on the front frame, two at the hub and two close to the tip. The two outer hinges required mounting pedestals which extend from the strut leading edge. These pedestals have a formed sheet metal box construction with a solid hinge point set into the top section and attaching directly to the leading edge cap and side walls of the strut. Bulkheads within the strut serve to distribute the shear, bending, and torsional loads. Static tests up to a maximum load of 700 pounds in a transverse direction have been performed on the pedestals without any distortions to the surrounding structure.

Modifications to the hub to provide for the inner hinges consisted of the addition of four axial mounting pads. These pads are set in the top mounting plate and are supported by axial box-shaped gussets attached to the pads top plate and the cylindrical hub skin. Shank nuts are assembled under the pads to retain the hinge brackets.

Design changes in the hub were necessary to accommodate the door actuators and actuator brackets. Located in the hub are radial gussets for stiffening the hub cylinder and supporting the outer skin of the bulletnose. Partial removal of the four gussets adjacent to the major strut was necessary to provide clearance for the actuators and actuator mounting brackets, however the material removal was such that support for the bulletnose is still provided. Eight holes were added to the "record player", two under each gusset cutout, for attachment of the actuator mounting brackets. Provisions for the bracket securing nuts were also provided.

Selection of the "butterfly" inlet closures in preference to the earlier inlet louver design allowed the louver bushings to be removed from



the bellmouth and major strut. This change not only provided a smoother inlet flow surface but also reduced the frame weight and simplified the manufacturing operation.

The support beam design was changed to accommodate the double entry scroll and the accompanying change in loading to the frame. The earlier design had a separate support beam bolted to the end of the minor strut at the 3:00 o'clock position with angular shimming between the strut end and support beam to allow matching the scroll nozzles and rotor turbine buckets. In order to reduce the complexity, the support beam was designed as an integral part of the minor strut with the radial scroll adjustment provided at the scroll clevis. The new center mount location of the double entry scroll plus the structural arrangement of the XV-5A airplane allowed a shorter support beam providing additional weight savings.

Frame pickup points were provided to mount a circular inlet vane. From NASA Ames wind tunnel tests, fan aerodynamic and mechanical performance improvements during cross flow conditions were evident with the introduction of this inlet vane. Each vane assembly quadrant is mechanically connected to the frame at the struts and bullethead. A recessed rectangular pad was added to each sidewall of all four struts for attaching the ends of the circular vane, with an internal brazed box structure added to each strut wall to distribute the vane loading. Supports were added to the bullethead for the straight and bent vanes.

#### b. Inlet Vane

The inlet vane system used on the X353-5B lift fan was designed and developed as a result of static and wind tunnel tests of a fan-in-wing design. The inlet vane assembly, shown in Figure 18, consists of a full 360° circular vane concentric with the fan bellmouth and fixed side vanes parallel to the fan minor struts. The fan assembly has four (4) vane quadrants mechanically attached to the steel front frame.

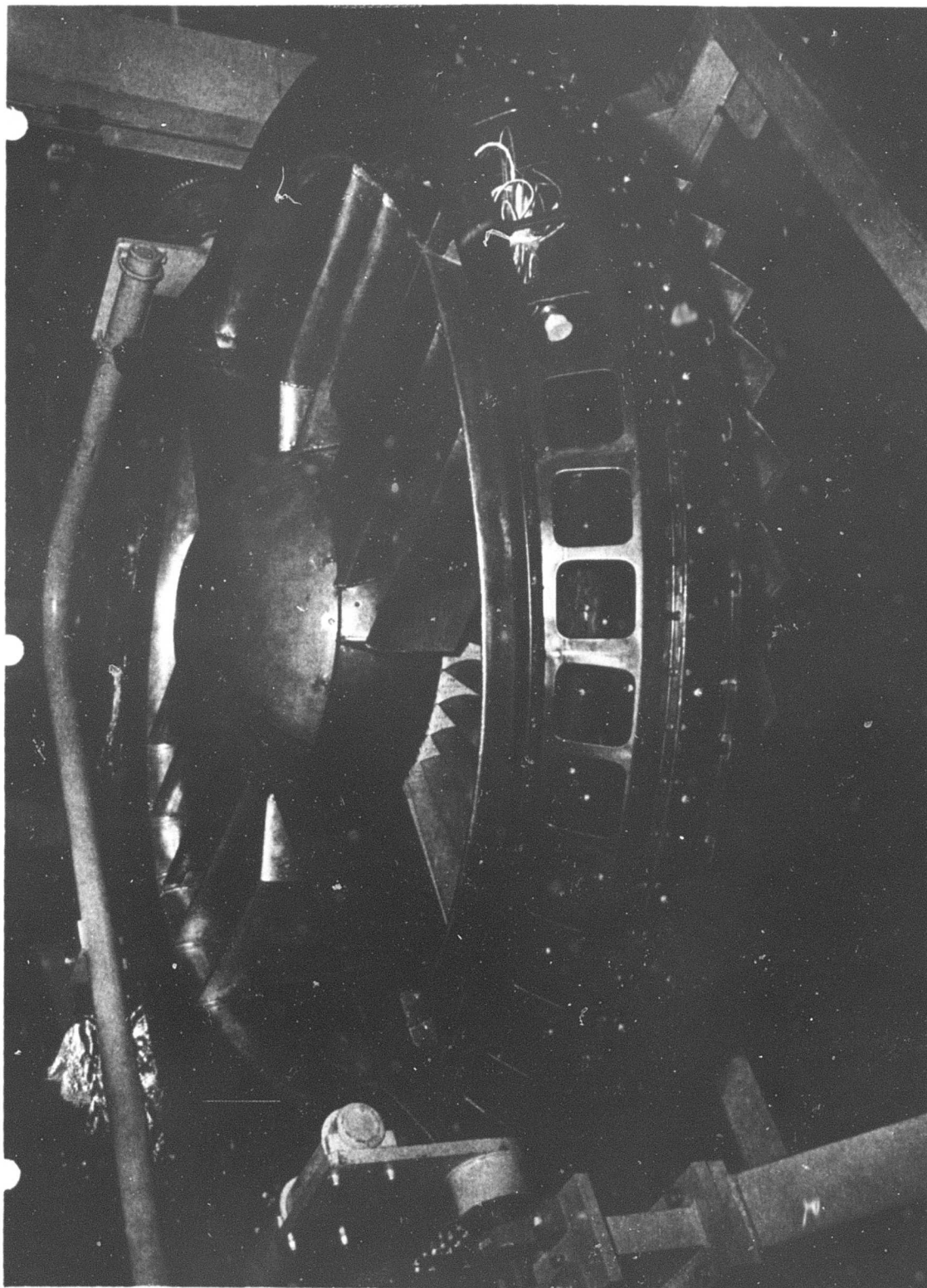


Figure 18. Circular Inlet Vane

The circular vane provides turning of the inlet flow into the fan and prevents flow separation from the bellmouth during hover. Tests have shown (AML Technical Report 62-21) that a 25 percent increase in hover performance has resulted through the use of the circular vane design. The problem was that in order to draw flow into the full inlet, very high velocities (on the order of 700 feet/second) occur on the bellmouth. Based on the flow analysis, this high velocity flow must diffuse to an average rotor entrance velocity of 435 feet/second. Since this amount of diffusion is marginal for stable air flow, separation could easily occur at the bellmouth or be caused by the seal leakage air entering the fan stream at the lower end of the bellmouth. The circular vane acts as a lifting surface whose force is directed toward the bellmouth lip, reducing the bellmouth lip static pressure and the flow velocity, keeping the flow attached to the bellmouth wall. The straight side vanes are the result of a program to minimize cross flow effects on rotor blade stress with minimal effects on fan performance (AML Technical Report 63-21). Magnetic tape data obtained at NASA Ames at 125 knots show at least a 10 percent reduction in blade flexural stress levels as a result of the straight vane addition to the inlet system.

The inlet vane geometry utilized during NASA Ames tunnel tests was a heavy (100 pounds/fan) non-flight type design and attempts were made to measure dynamic stresses, but little or no vibratory stress activity was noted. As a result of the NASA Ames data, a light weight aluminum vane design was selected for the XV-5A program. Steady state (static/stress) analysis was completed on the basis of aerodynamic loads predicted from tests on a scale model fan. These data were presented on a completely attached flow basis and were felt to be conservative or higher than would be encountered in actual cross flow operation.

The inlet vane assembly was constructed from formed sheets (0.030") of 61ST4 aluminum. The two sheets were welded together at the leading and trailing edges to form the basic airfoil contour. The material was selected for its weldability. Considerable effort was expended in the manufacturing

shops and at Alcoa Research Laboratory to develop a welding process that could be followed by a simple 18 hour age at 325°F. This effort was felt to be required to eliminate potential distortion that could be encountered by following the standard recommended post weld heat treat (960°F water quench plus 8 hours age at 350°F).

During the XV-5A flightworthiness tests at General Electric, Evendale, the inlet vanes developed cracks which were attributed to inadequate weld processing technology. The weld process and vane design were modified. Subsequent tests, including specified penalty runs, were completed without recurrence of previous failures. Ground tests at Ryan, Edwards Air Force Base, and NASA did not produce any failures in any of the 16 quadrant populations on the two aircraft.

In May 1964, Aircraft #1, containing lift fans - S/N 005 and 006, was installed in the 40 x 80 foot wind tunnel at NASA Ames. After approximately 4 hours of tests up to 80 knots, the forward inboard quadrant on the left hand fan broke loose at the forward 12 o'clock mount and deflected into the fan rotor. The tests were summarily stopped pending analysis and repair of the inlet vane design.

Detailed review of the damage and microscopic data indicated that three failure areas were present:

1. Circular vane trailing edge crack
2. Straight vane attachment to circular vane attachment cracks
3. Possible low strength material at the vane mounts.

A review of the steady state stress analysis showed a maximum stress of 8800 psi on the circular vane convex side between the straight vane attachments (no failure).

It was concluded that the vane in its as-designed condition had manufacture and material deviations that resulted in cracks after short

time loading in the higher cross flow fields. The loading (steady state or dynamic) could result in cracks that would propagate in the dynamic field. Accordingly, permission was received to modify two sets of inlet vanes (not previously run in cross flow) to remove the noted vane deficiencies. Modification I consisted of a row of bucked rivets along the circular vane trailing edge, the addition of welded brackets improving the straight vane attachment at the circular vane, and heat treat to get T6 properties.

The Modification I vanes were installed and tested at 2300/2400 fan RPM to 60-80 knots for  $1\frac{1}{2}$  hours without failure. However, after approximately 2 minutes at 2500 RPM and 100 knots, the tests were stopped and inspection revealed a series of spot weld cracks in the straight vanes and circular vanes where an internal channel section had been attached as part of the design to handle in-plane shear loads, and to help the airfoil maintain its section modulus. These cracks were regarded as another incidence of stress concentration failure in the welded portion of the vane. It was significant to note that after tests at higher loads and time than before, the original failures were not realized. The same eight quadrants were changed to Modification II status by the addition of a 0.030" 61ST6 aluminum doubler placed circumferentially over the spot weld joints. The doubler was attached with epoxy resin and cherry rivets.

Tests were resumed. Inspection after 41 minutes, 2400 RPM and 60 knots showed no damage. Inspection after 10 minutes, 2500 RPM, 100 knots showed no damage. Inspection after 30 minutes, 2500 RPM, and 100 knots showed cracks in the straight vane that has the bent leg for dome attachment. These cracks occurred in two quadrants and were in the weld at the vane leading edge. No additional tests were performed due to shutdown for tunnel repair. Further inspection of the vanes showed no recurrence of original failures, and no further evidence of spot weld cracks. It was concluded at this time that the existing vane design (as modified), material, and fabrication did not have sufficient capacity for sustained high speed, high cross flow loading.

Continued modification would extend the part life for a frequent inspection 50 hour flight test program, but follow-on 100 hour test programs would require a design utilizing materials and processes that had sufficient capacity for the dynamic loading in transition flight modes.

Inlet vane Modification III was a continuation of efforts to remove or reduce the effects of weld fabrication stress concentrations in the assembly. The vane quadrants selected for this modification were new-unused pieces of hardware; hence, there was an opportunity to improve the basic Modification II design as well as initiate Modification III. The Modification II improvements are simply more quality control, uniformity, wider spot weld reinforcement doublers, and beveled edges on welded reinforcement pads (straight vane/circular vane) to optimize weldability. In Modification III, the fix was extended into the areas of the mounting pads, more efficient joint design at the straight vane/circular vane, backup of welded areas at mounts with rivets and reinforcements to improve the in-plane shear load distribution into the mounts. The most significant change in the Modification III vane occurred as a result of extended steady state stress analysis. The 3 o'clock mount has been changed from a fixed to a pinned (uniball) mount. Stress analysis data indicates a significant drop in steady state loading as a result of this change. This is best explained by a quick review of the vane design. The vane quadrant principal loads occur as a result of (1) air loading of the vanes, and (2) axial deflection of the front frame bellmouth. The fan mounting arrangement permits the outboard end of the minor strut to rotate about the major strut axis as a result of bellmouth aerodynamic loading and rotor gyro maneuver loading. The inlet vane original design included a pin at the 12 o'clock and 6 o'clock positions to eliminate high bending loads induced as a result of the frame deflection. The 3 o'clock and 9 o'clock mounts were rigidly bolted to the minor struts.

Modification III and the steel vane designs both use the pinned (three direction) mount. The reduced steady loads and resultant higher dynamic capacity should result in a significant increase in inlet vane life and mechanical integrity.

## 2. ROTOR

### a. Bucket Carrier Construction

The X353-5B bucket carrier is a brazed fabricated structure utilizing sheet metal and machined bar materials. Original carrier construction, based on cost and weight studies, indicated that better control could be obtained by machining separate side rails and cross beams. These elements would be joined by braze to form the basic structure of the bucket carrier. Subsequent manufacture of these parts proved that the braze joint interface between the side rails and cross beams was sufficiently large to cause some difficulty with the braze alloy. The difficulty resulted from the need for a single braze alloy which exhibited filleting, capillarity, and compatibility with base material mechanical properties. The problems were successfully resolved but required a high degree of process control.

The manufacture of the carrier component by machining an integral side rail-cross beam structure from a forged bar was developed from the vendor's previous experience. The use of this process resulted in cost reduction and elimination of the braze difficulties encountered on the prototype pieces. The machined bar approach was used on all carriers procured for the XV-5A program.

### b. Segmented Torque Bands

One basic torque band design provides torque transmission at the blade tips to the compressor blades not in the hot turbine gas admission arc. The configuration developed during the X353-5A program was two

360° rings made of .045 thick R41 material. The rings utilized a series of radial tabs which were bolted to the turbine bucket carriers. This configuration was demonstrated successfully without failure during simulated XV-5A airplane tests in the NASA Ames wind tunnel.

Shortly after the start of flightworthiness tests for the XV-5A program, the torque bands buckled and finally cracked at the buckle during subsequent fan operation.

An analysis of data, including the successful demonstration of the torque transmitting capacity of a single band across the joint of adjacent bucket carriers, resulted in a decision to segment the bands. Six sectors were chosen to eliminate possible interaction of rotor tip boundary condition with four node mode of rotor axial vibration.

The segmented band design was directed toward reducing stack up dimension problems and resultant buckling loading on a hot band during shut down.

A review of torque band condition at the completion of the flightworthiness tests resulted in two additional changes affecting the torque band component. First, a 0.005 inch thick coating of copper nickel indium has been added to the band outside diameter at the tab spanning adjacent bucket carriers. The metal spray coating becomes an agent to reduce or eliminate fretting damage to the band. Second, the torquing procedure for bolting the bands to the carrier has been changed to place the high torque value on the carrier side adjacent to the segment end. Data have shown that this becomes an effective means of transmitting torque through the carrier body. This reduces the loading in the continuous band side of the joint and consequently reduces the strain displacement and fretting damage.



### c. Dovetail Stress Analysis

X353-5B lift fan compressor blades utilize a single hook dovetail design for attachment to the disc. The single hook dovetail form was introduced into the X353-5A program with the re-orientation blade and was initially demonstrated in NASA Ames wind tunnel tests.

The change in dovetail form was completed when it became apparent that the original 3-hook form did not have sufficient load capacity in the rotor system modes of vibration (Gyro, Cosine 2 $\theta$ ). The new single hook form has been extensively analyzed at rotor speeds and vibratory modes encountered during all phases of X353-5A test programs.

Dovetail stress analyses are based on design tools complemented by bench tests. Analytical tools have been tested by selection of a form being utilized in other General Electric propulsion systems now in operation. The application of this form to XV-5A materials and blade/disc geometry were studied by combined load-bench tests. Holding blocks of disc material and portions of actual blades were procured and set up in a test rig where both steady state and dynamic loads could be varied. The test program had three important inputs to the XV-5A program.

1. The graphite-resin coating applied to the X353-5A 3-hook dovetail to inhibit fretting was unsuccessful under loads and life required to test the dovetail to its limits.
2. The application of a metal spray coating (copper nickel indium) was demonstrated and proved to be much superior to the graphite-resin.
3. Dovetail joint tests about maximum moment of inertia axis at 105% rotor speed load has demonstrated sufficient capacity to withstand any stress level encountered to date in the

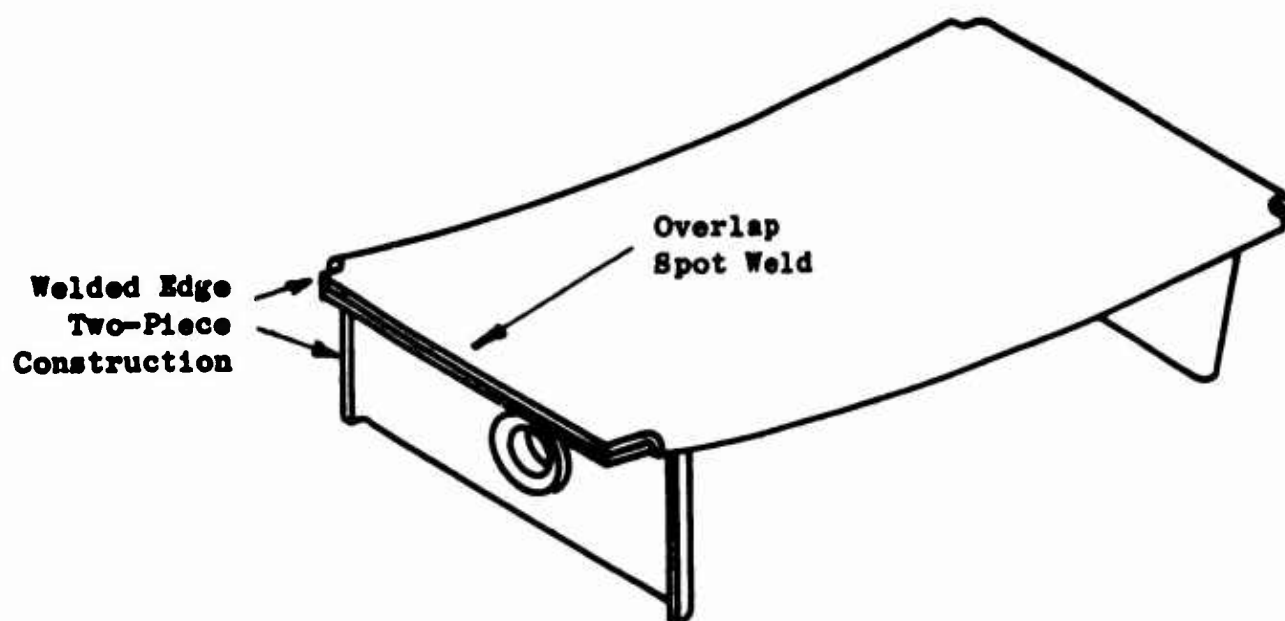
X353-5A and X353-5B test programs. Although the bench tests did not demonstrate full design load capacity of the dovetail joint, further tests were postponed until XV-5A experience warranted such effort.

#### d. Torque Band/Carrier Bolts

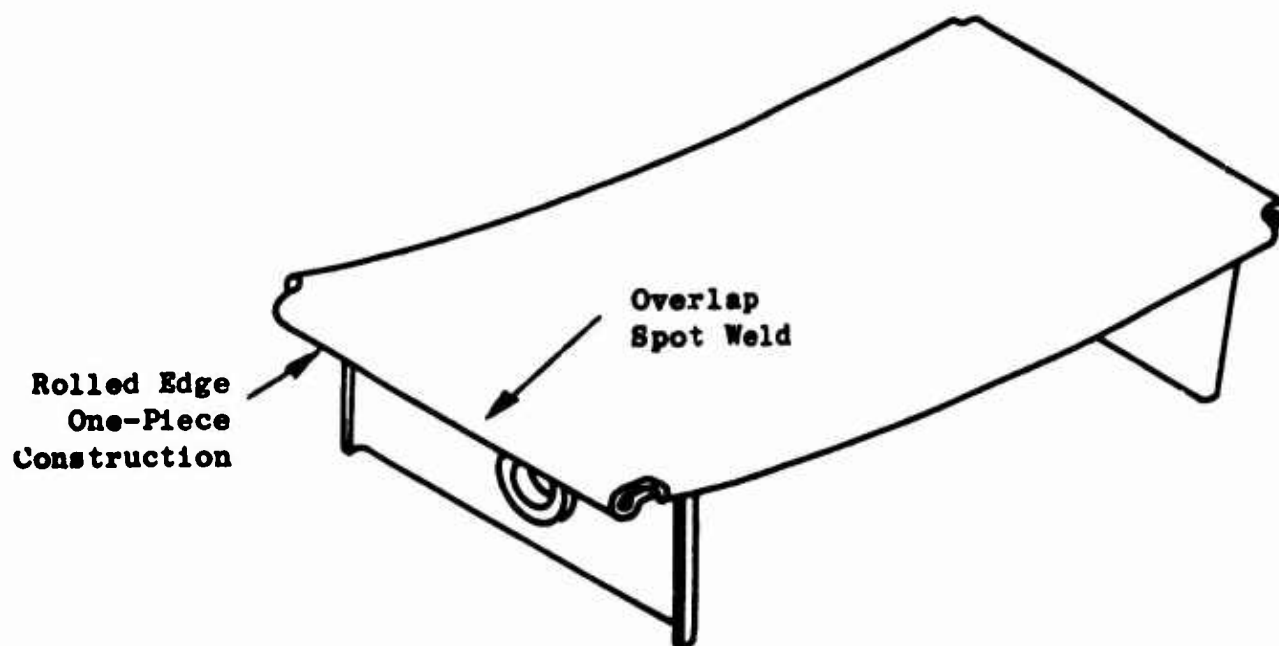
The two-piece torque band seal design provides sufficient space to utilize a shank on the torque band/carrier bolt. Studies were made and a common bolt was selected to replace the old full thread torque band bolt and the low temperature stainless steel shank bolt used to hold the blade platforms. This change resulted in an A-286 material bolt to hold the platform but eliminated the requirement for one bolt series in the X353-5B fan rotors.

#### e. Blade Platform

The lift fan rotor uses a welded/fabricated aluminum structure to form the flow path at the blade root. The new dovetail design, discussed in prior paragraphs, resulted in an increase in the disc rim width from 2.00 to 2.25 inches. To keep the design within acceptable welding process standards, the platform structure was altered as shown in the top sketch of Figure 19. This design resulted in a weld joint along the platform leading edge. During the last phase of Ames testing, one of the redesigned platforms failed. Subsequent examination revealed that the cause was a faulty weld. It was felt that this single failure was an indication that the design was too sensitive to weld process control and thus would require an expensive proof test program to ascertain the quality of XV-5A hardware. Accordingly, the design was changed back to the original X353-5 approach and the XV-5A components were based upon the successful experience in the X353-5 program.



UNSATISFACTORY DESIGN



DESIGN FOR XV-5A

Figure 19. Blade Platforms

### 3. SCROLL

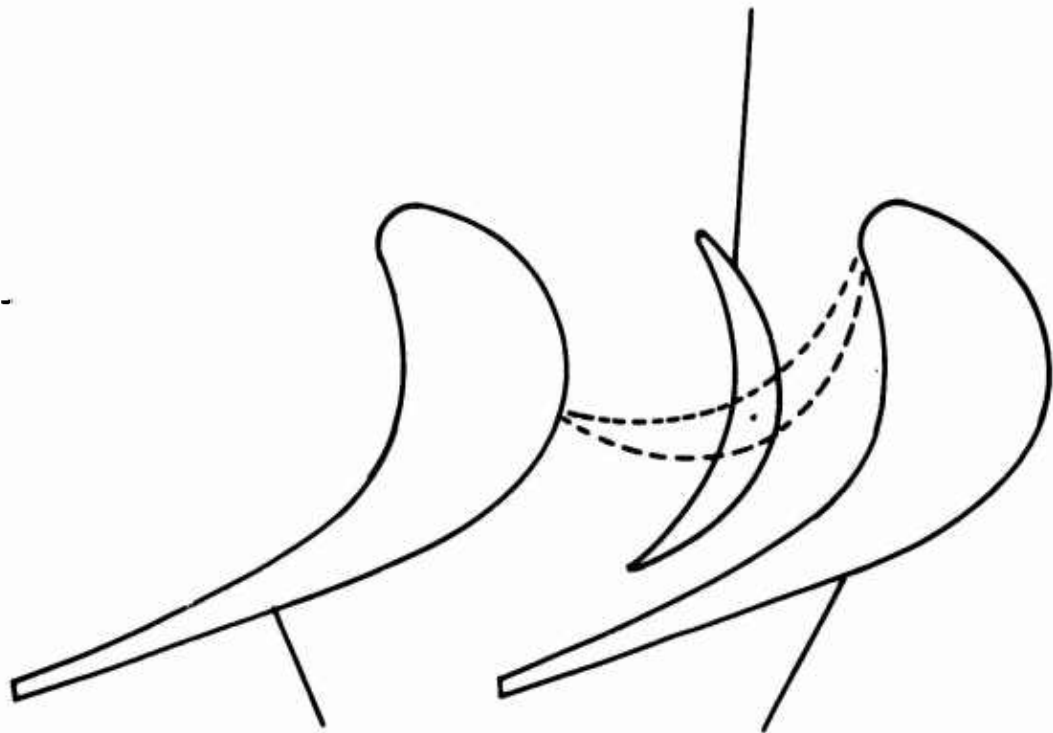
The scroll was redesigned to provide two scroll halves with separate inlets for the XV-5A cross-ducted installation. With this arrangement, each turbojet delivers half the driving power for each lift fan permitting half power operation of all fans in an "engine out" situation.

Scroll nozzle area trim devices were added which provide adjustment of nozzle area of up to 22 percent of the maximum area. This trim is accomplished by means of splitter vanes between nozzle partitions at the ends of the scroll arms as shown in Figure 20. These vanes can be individually rotated from a streamlined position through four incremental steps to full blockage of the passageway. Thus a fine degree of area control is possible. The area variation is provided to allow matching of nozzle area to turbojet engine characteristics, in order to provide compensation for pressure loss variations in the cross ducts, and to allow balance of lift in right and left hand fans.

Scroll material was changed from L605 to Hastelloy X to reduce weight. Detailed comparisons of material properties and manufacturability indicated that a ten percent weight reduction could be realized without sacrificing strength. The characteristics of the materials are sufficiently alike at the scroll operating temperature to allow a direct substitution without any dimensional changes. The slight reduction in Young's Modulus is not considered serious in view of the high buckling safety factors in the design and the small scroll deflections under load.

In order to reduce the flow path distortion and poor dimensional control at the scroll nozzle area that was encountered during previous manufacture, the nozzle partition and strut assembly was changed from an all-brazed assembly. Prior to any braze alloy selection, several alloys were evaluated to insure that satisfactory joints and joint strengths could be obtained. The elimination of the weld shrinkage from this assembly provided a more stable and distortion-free part.

**Moveable Area Trim Splitter Vane**



**Fixed Scroll Nozzle Partitions**

Figure 20. Area Trim

Minor skin buckling on the scroll underside between the inlets was observed during initial development testing. In order to insure that the buckling would not progress and cause excessive scroll deflections, a hat section was added to the affected section.

#### 4. REAR FRAME

Minor changes were incorporated to improve the manufacturability of the rear frame, consistent with the need for changes observed during the fabrication of the original two frames. These changes were limited to minor dimensional errors and interchangeable processes found more favorable during manufacture.

The primary design change in the basic rear frame was the addition of another compressor vane support ring. Analytical study revealed that this was the best solution to eliminate vibratory response of these vanes in certain operating ranges. The addition of one ring and the asymmetric spacing of these rings eliminated stator resonant situations.

The rear frame exit louver actuation system was redesigned to incorporate all linkage inside the rear frame strut. Two actuating push rods are used, one actuating from each end of the strut. Exit louvers are connected alternately to one push rod and the other to permit staggered louver operation.

Splined arms and shafts have been substituted for the original "shaft with flats" design in the actuation linkage to increase torque capacity of the system. This alleviated the exit louver actuation wear problem seen during wind tunnel testing under contract DA 33-177-TC-584.

Initial aircraft flight and wind tunnel testing indicated that aerodynamic loading was considerably higher during maximum louver stagger angles than originally calculated. This increased loading (an increase of 200%) created a major redesign of the push rods and rear frame attachment for the actuator brackets.

### Rear Frame

The rear frame was modified by the addition of a lug which was plate-welded to each side of the strut at both fore and aft ends. The added lugs were adequate for tensile loads but to prevent panel buckling of the strut skins from compressive loading, 0.048 inch plates were attached to the strut sides.

### Cam and Rod Stops

In addition to a new louver link for increased moment arm, a cam surface was designed into the link to prevent the exit louvers from clashing during full stagger operation. A material change to Marage steel was made for a yield strength increase of 2.5 above the original material. Mechanical stops were also incorporated on the push rods to limit the differential motion between the push rods. These mechanical stops would also prevent clashing of the louver tips in the event that a cam failed to function properly.

### Push Rods

The forward actuated push rod was changed from a "U" channel to a solid rod with slots machined to accept the internal louver linkage. Buckling strength was increased by a factor of 3 over the original design. The aft actuated push rod remained a "U" channel but with stiffener ribs brazed to sides. Buckling strength was increased 25%.

Failures of the aluminum exit louvers during the flightworthiness test has been traceable to improper manufacturing process control related to welding. Spot welding of 6061 aluminum is extremely difficult, requiring rigid control of material and electrode tip cleanliness as well as machine schedule. Minor deviations in any of these areas can cause poor welds, from no nugget formation, to burning, excessive pickup, or cracking. A redesign was initiated to provide sufficient integrity such that minor spot

weld defects could be acceptable without impairing design requirements. Figure 21 shows the redesign of the internal structure at the actuation attachment end of the louver. Four rivets were added and the doubler plates were extended along the ribs, thus spreading the actuation loads further into the louver body. Eight additional rivets, extending through the louver, provided a mechanical tie of the skin to the internal structure thereby reducing the need for 100% spot weld requirement in this area. A successful penalty flightworthiness test was completed with the louvers modified in the above described manner.

During ground testing of the XV-5A aircraft at Edwards Air Force Base, several factors affecting roll control were discovered all of which detracted from the inherent fan roll power. One factor visually observed was the deflection of fan exit louvers due to air loads generated by the fan at high stagger angles. Reduction of these deflections by increasing structural rigidity of exit louvers allows an increase in aircraft roll control power to be realized.

Although the same basic airfoil shape is used throughout, two different types of louver constructions are used in the assembly. This is brought about by the very small degree of mixing occurring between the "cold" fan air and the "hot" turbine discharge gases. Aluminum louvers are used in the cold fan air and steel louvers in the hot turbine discharge gas. Both sets are interconnected to insure they vector and spoil the same amount simultaneously. This arrangement allows a satisfactory lightweight design to be achieved without sacrificing the structural integrity of the louver system. The basic airfoil shape for both designs is manufactured from a single formed sheet, bent around the leading edge and seam welded along the trailing edge. Internal stiffening is provided in the form of "U" channels which extend the full length of the vanes. The materials selected for the two designs are 0.03 thick 6061-T6 for the aluminum louvers and 0.02 thick Inconel X for the steel louvers.



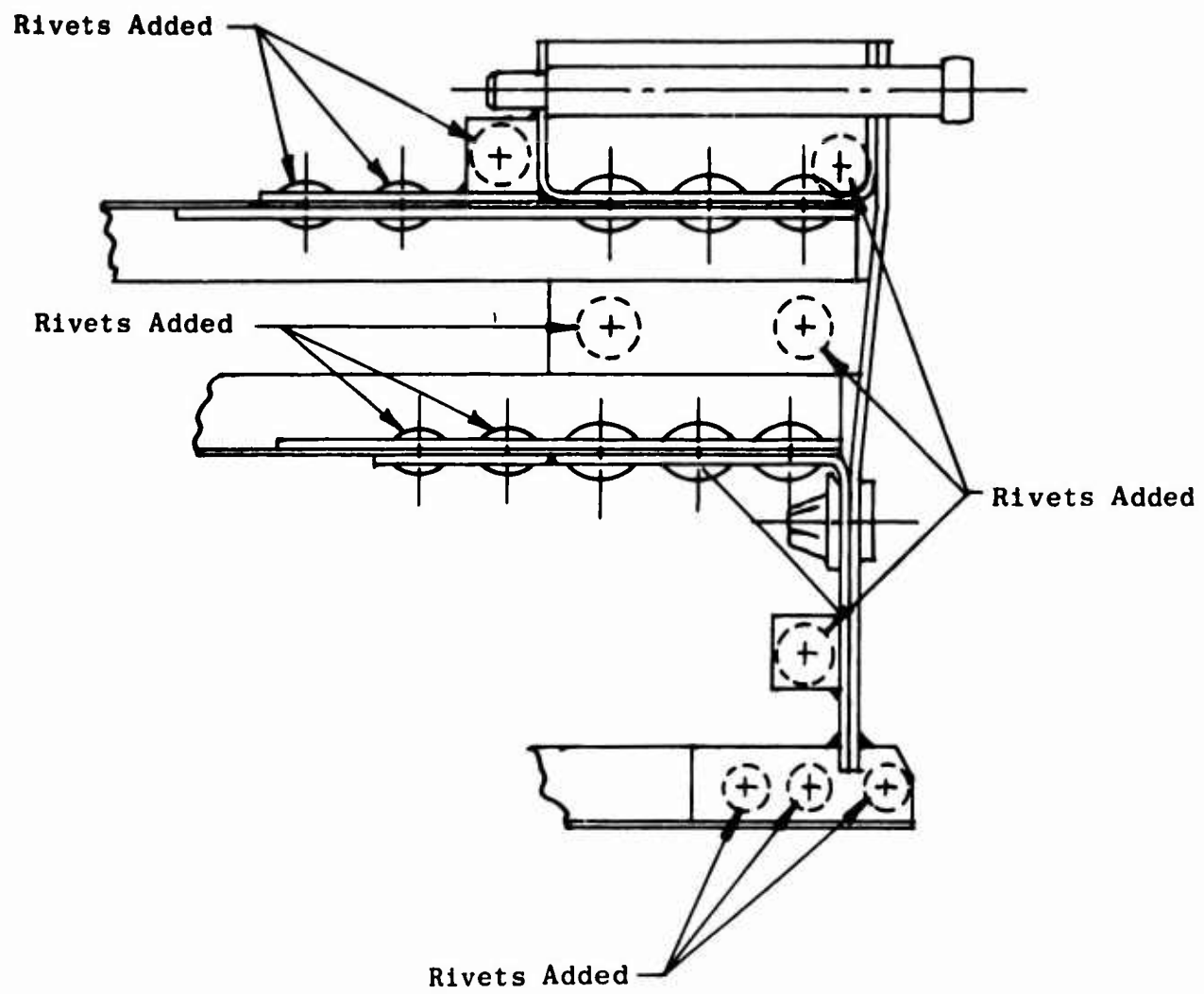


Figure 21. Louver Actuation Attachment Redesign

The adequacy of these designs to withstand the gas loads was proven during the flightworthiness testing conducted at the Contractor's Plant commencing in December 1962. Although cracking and failure was experienced at the end connecting to the push rods, the louvers successfully completed specified penalty runs, after a design improvement was incorporated at the push rod end, without a recurrence of the previous failures.

During the portion of the Edwards ground testing when the push rods were firmly held by load links, significant deflections were observed in the aluminum louvers. Figure 22 shows the deflection of the longest louvers under the influence of the gas loads. Tests to measure these deflections show that for a stagger angle of  $39^\circ$  and 100% fan speed, the angle of twist of the louver is  $5.3^\circ$  and at a vector angle of  $13^\circ$  the untwist is less than  $1^\circ$ . Although these deflections are not detrimental to the structural integrity of the louvers nor do they affect the  $1.06 \text{ radians/second}^2$  roll acceleration obtained during flightworthiness testing, their reduction or elimination would increase thrust control effectiveness to either add a margin of control reserve or compensate for deficiencies elsewhere in the control system.

The longest louver in the "cold" side was analyzed by the method of superposition to evaluate the deflections under the influence of the fan air loads. The air loads were assumed to be uniformly distributed along the span of the louver with a chordwise distribution given by:

$$\Delta_p = 1.33 \quad 1.1 - [(A_j/A)^2]$$

Where  $\Delta_p$  is in psi, 1.33 is the pressure rise at 100% speed,  $A_j$  is the area at the trailing edge between the consecutive louvers and  $A$  is the area at any chordwise location between two consecutive louvers. The method was:

1. Calculate the maximum deflection assuming that the louver is simply supported at each end.



Figure 22. Louver Deflection

2. Calculate the maximum torsional deflection assuming the louver to be fixed at the strut end.
3. Assume the louver is fixed along the leading edge and calculate the deflection of the trailing edge.

By combining the results of (1), (2), and (3), a deflection curve along the trailing edge can be found. No attempt was made to include the effects of shear lag or warping in the analysis; both of which act to make the louvers more flexible. Inclusion of these two factors would have brought the analytical result closer to the actual case. The results show a maximum angle of twist of  $3.47^\circ$  as compared to the  $5.3^\circ$  measured at Edwards.

As a result of this analysis, it was decided that the best way to modify the louvers would be to increase the effective skin thickness by putting another skin over the outside. Accordingly, the bow and twist would be reduced by more than half of the previous values. The method used to take a formed outer skin of the same stock thickness and material as the louver and adhesively bond and rivet it to the louvers.

## B. X376 PITCH FAN

### 1. AERODYNAMIC DESIGN

#### Summary

The basic fan aerodynamics of the pitch control fan were taken directly from the developed X353-5A lift fan. Some modifications were made which are not directly a result of size scaling. These modifications were generally minor but the most significant changes were tested in a low speed scale model of the pitch control fan. Subsequent development testing, both statically and in the full scale model wind tunnel tests, showed no major deficiency.

#### a. Fan Aerodynamic Design

The aerodynamic design of the pitch control fan is taken directly from the X353-5A. The major changes are a higher rotor radius ratio and new bulletnose shape, and the entirely different installation of the fan. The design speed (4075 rpm) was selected so that the corresponding tip speed (640 feet/second) was 89 percent of the X353-5 design tip speed (720 feet/second). The size is scaled to a 36 inch fan rotor tip diameter from 62.5. The size change and radius ratio change are such as to reduce the fan thrust at the same tip speed by a factor of .315. The aerodynamics of the X353-5A was selected instead of the X353-5B because the former runs at a higher speed at a given power. This is in the direction to improve the turbine efficiency which would otherwise be reduced due to a lower tip speed.

The radius ratio of the pitch control fan was increased from 0.4 to 0.45. The rotor and stator blading at the hub of the pitch control fan is identical to that at 0.45 radius ratio on the X353-5A. The hub contour of both is cylindrical in the vicinity of the rotor and stator. An 0.45 radius ratio low speed scale model of the pitch control fan was tested for any changes in flow, power consumption, throttling characteristics, and efficiency as a result of the change. Further testing reported elsewhere in this report evaluated the effect on fan operation of the changed installation and environment improved by the inlet upstream and the reverser downstream.

The following is a tabulation of other changes which are related to the aerodynamic operation of the fan:

1. Reduced rotor tip thickness/chord ratio to 0.048
2. Eight struts ahead of rotor (vs 4 in X353-5B)
3. Increased stator chord and increased stator aspect ratio  
(same physical chord in both fans)
4. Sheet metal stator support ring. This was previously evaluated as an aerodynamic improvement over the strut-shaped support ring of the X353-5.

All of these features were evaluated as having negligible effect on pitch control performance.

## b. Turbine Aerodynamic Design

### Design Objectives and Requirements

The pitch fan is powered by bleed gas from the J85 engine. Two separate inlet scrolls are provided so that one half the gas flow is supplied by bleed from each of two jet engines. The design point is at 2500 feet on a  $93.7^\circ$  day, and the design net thrust is 1300 pounds. The scrolls are sized, however, to allow thrust growth to 1500 pounds by increasing the turbine flow. Table III presents a summary of the important turbine design parameters. The turbine inlet pressure shown assumes an 8.8% pressure drop from the diverter valve exit.

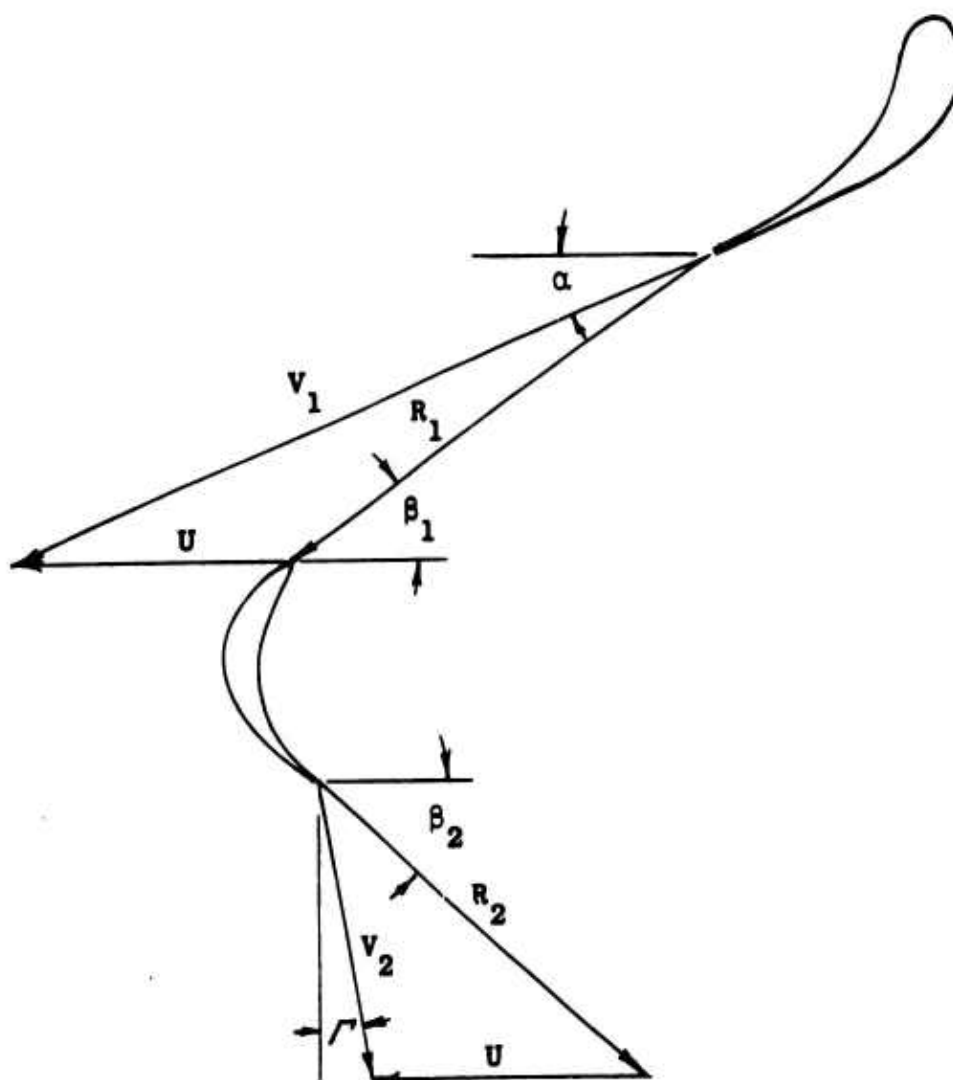
### Design Details

Figure 23 shows the design point vector diagram at the pitch line. The vector diagrams at the root and tip of this turbine are not significantly different from that at the pitch line because of the short bucket height and because the flow path has been designed to produce a constant gas velocity and angle at the nozzle exit plane. The turbine is designed to have an efficiency of .753 at its design point including partial admission and leakage losses. Table IV gives a breakdown of the turbine available energy and a comparison with the X353-5 lift fan turbine. It can be seen from this comparison that the largest single difference between the two turbines is the rotor loss. Two reasons exist for this: First, the X376 turbine is designed at a lower velocity ratio (.363 versus .411) so the bucket relative velocities are proportionately higher; second, the bucket is shorter and has lower than optimum solidity so that the bucket efficiency is lower. The nozzle loss and fraction of leakage are higher because of the proportionately shorter blade heights. The swirl loss is

TABLE III

X376 Design Parameters

	<u>1300</u>	<u>1500</u>
Net Fan Lift, lbs		
Inlet Total Temperature,	1710	1710
Inlet Total pressure, psia	24.48	24.01
Inlet Gas Flow, lb/sec	7.96	9.60
Inlet Flow Function	13.446	16.534
Total to Static Pressure Ratio	1.811	
Total to Total Pressure Ratio	1.661	
Exhaust Static Pressure, psia	13.514	
Exhaust Total Pressure, psia	14.735	
Speed, RPM	3794	
Design Power, HP	472.0	
Design Energy, BTU/lb	44.95	
Leaving Axial Mach Number	.360	
Impact Efficiency	.753	
Pitch Wheel Speed, fps	652.7	
Stage Velocity Ratio	.363	
Work Function,	1.321	
Tip Diameter, in.	40.864	
Hub Diameter, in.	38.000	
Bucket Length, in.	1.432	
Annulus Area, in <sup>2</sup>	71.633	
Admission Arc, degrees	145.44	178.8



$V_1 = 1769 \text{ fps}$	$M_1 = .953$	$\alpha = 22.52^\circ$
$R_1 = 1193 \text{ fps}$	$M_{R1} = .642$	$\beta_1 = 34.62^\circ$
$R_2 = 1026 \text{ fps}$	$M_{R2} = .548$	$\beta_2 = 41.08^\circ$
$V_2 = 685 \text{ fps}$	$M_2 = .366$	$\gamma = 10.13^\circ$
$U = 652.7 \text{ fps}$	$M_f = .360$	

Figure 23. X376 Turbine Design Vector Diagram



TABLE IV

Comparison of X376 to X353-5 Losses as a Percent of Ideal H. P.

	<u>X376</u>	<u>X353-5</u>
Shaft output	75.3	82.4
Nozzle diaphragm loss	4.1	3.4
Rotor loss	14.2	9.2
Swirl loss	0.5	0.0
Leakage loss	2.3	1.2
Windage loss	2.3	3.0
End loss	<u>1.3</u>	<u>.8</u>
Total	100.0	100.0
Exhaust energy	15.9	11.3

also higher with the partial admission losses being less because of the lower velocity ratio. The exhaust energy of the X376 turbine is higher than the X353-5 turbine but this is not considered a loss since this higher exhaust energy results in increased turbine lift.

Figure 24 shows the turbine flow path. The flow path through the nozzle blends to the scroll on the upstream side and is curved in an outward direction to eliminate radial static pressure gradients downstream of the nozzle. The flow path through the buckets and stators is essentially cylindrical, however, the stator tip radius is substantially larger than the bucket tip radius. This discontinuity in the tip radius was made to simplify construction and is not considered to be a serious detriment to turbine performance or thrust.

Figures 25, 26 and 27 show the nozzle partition profiles. Profiles of families I and III are used in opposite arms of each scroll where the flow entering the nozzles has a rather high tangential velocity component. Profiles of family II are used directly in the center of each scroll where the flow is more nearly axial. From a point just upstream of the throat, the suction surface of all three nozzle profiles is geometrically similar. Also the ratios of throat dimension to spacing are the same. These nozzle profiles are very similar to those used in the X353-5 fan turbine except that the profiles have been modified slightly to conform to slightly different vector diagram angles.

Figure 28 shows the bucket profile. This bucket differs from the X353-5 bucket and Table V gives a comparison of several important aerodynamic parameters. The solidity of this bucket is 20 percent lower than that of the lift fan bucket for two reasons. First, cascade tests of airfoils similar to this design has indicated that a slightly lower solidity than that used on the lift fan bucket was nearer to optimum. Second, for weight considerations, the decision was made to utilize a lower than optimum solidity at a small expense of performance.

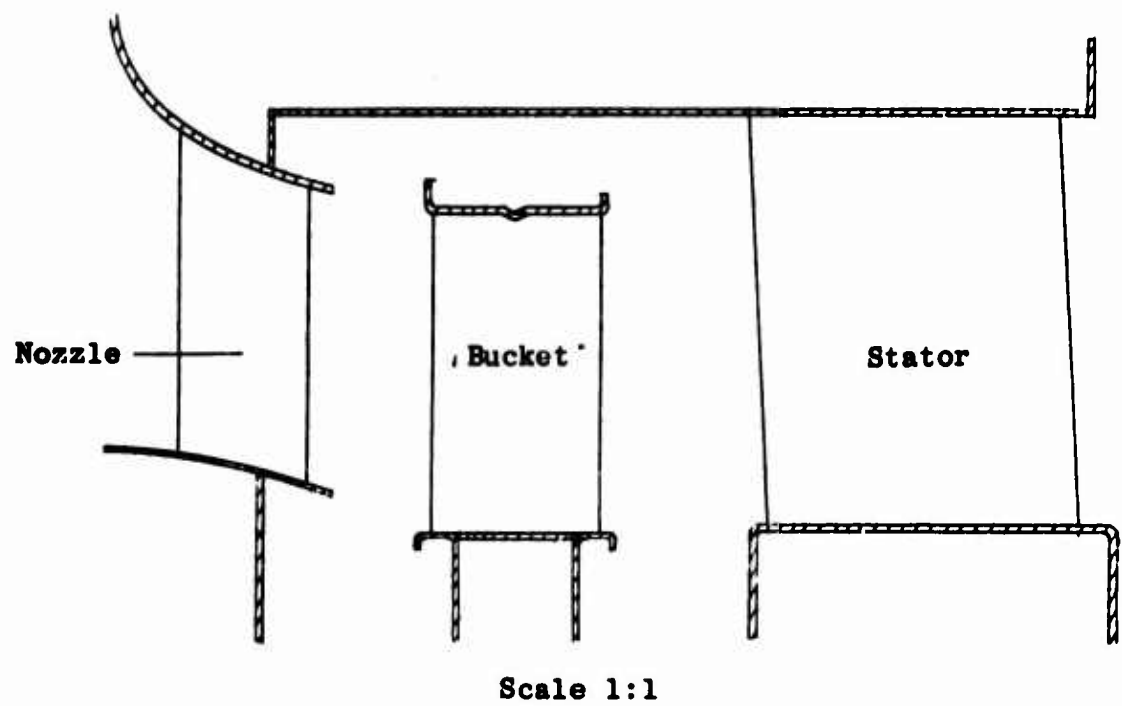
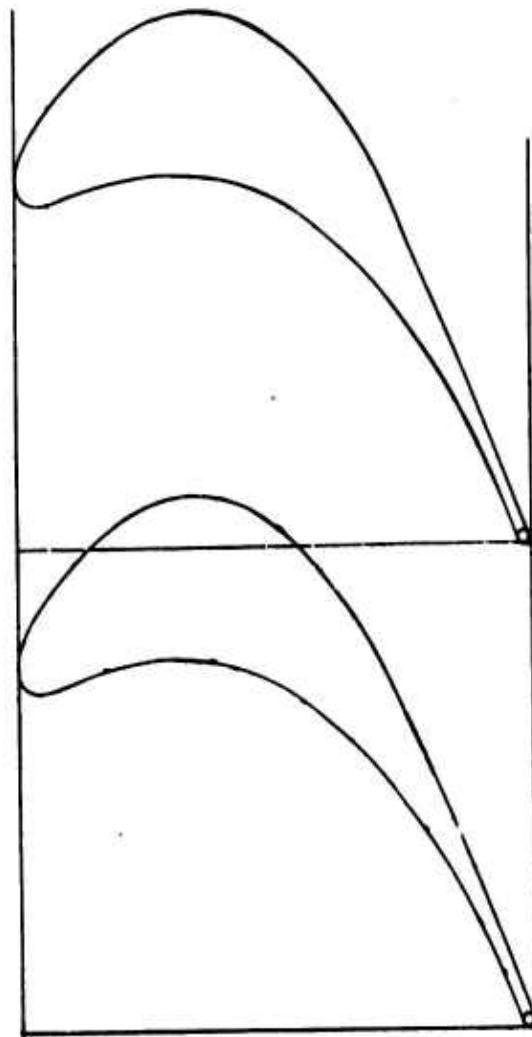
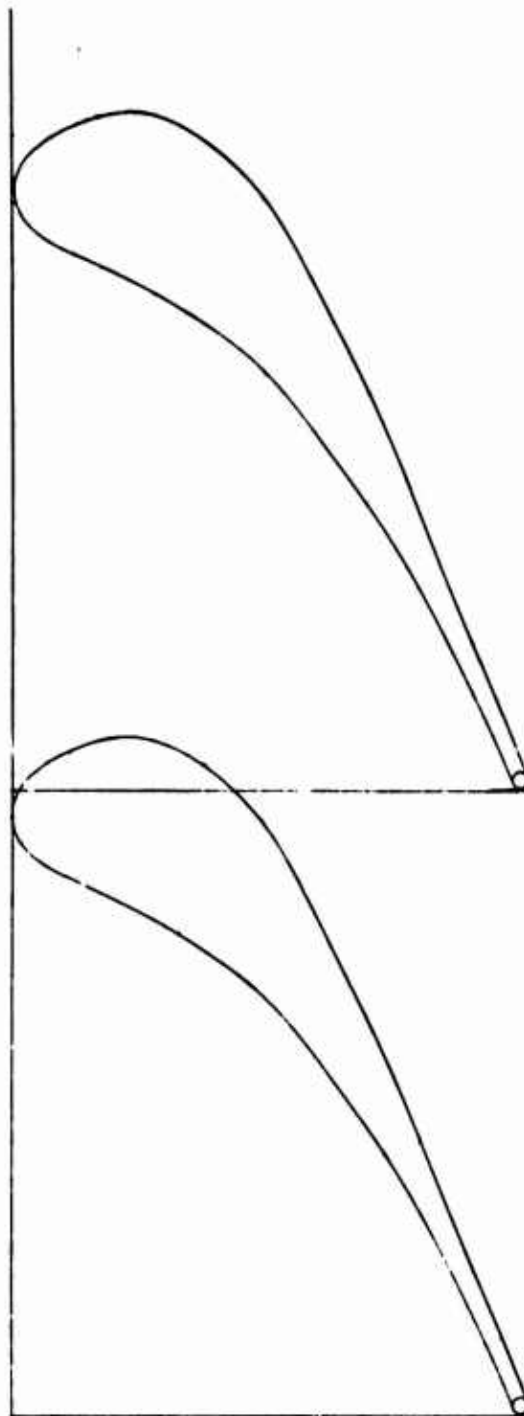


Figure 24. X376 Turbine Flow Path



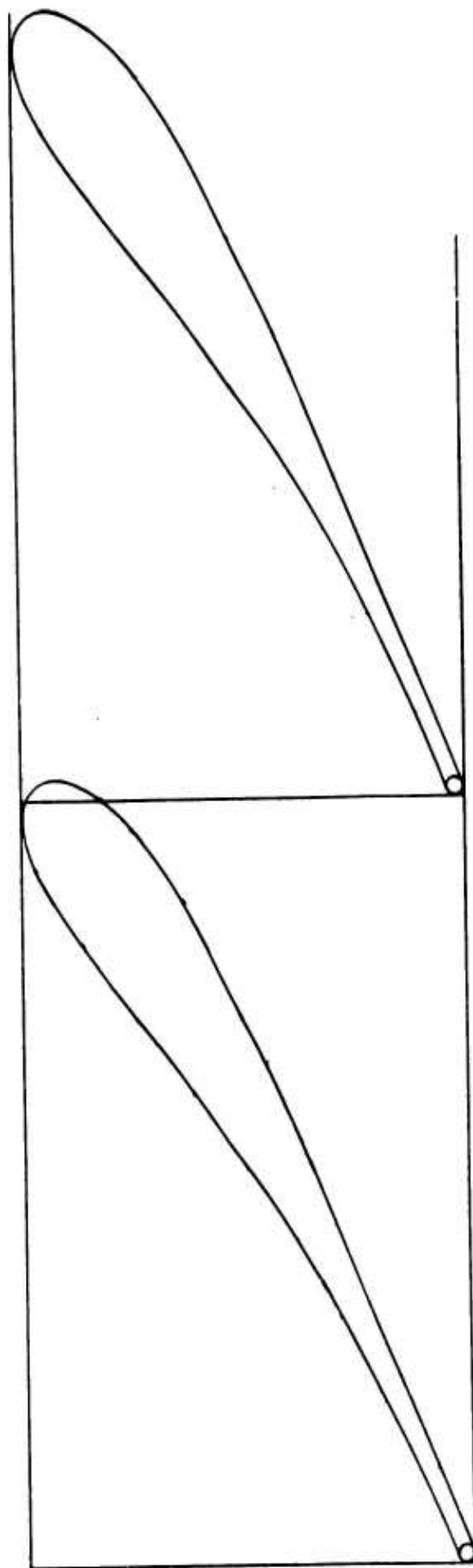
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Figure 25. Nozzle Profile Family I



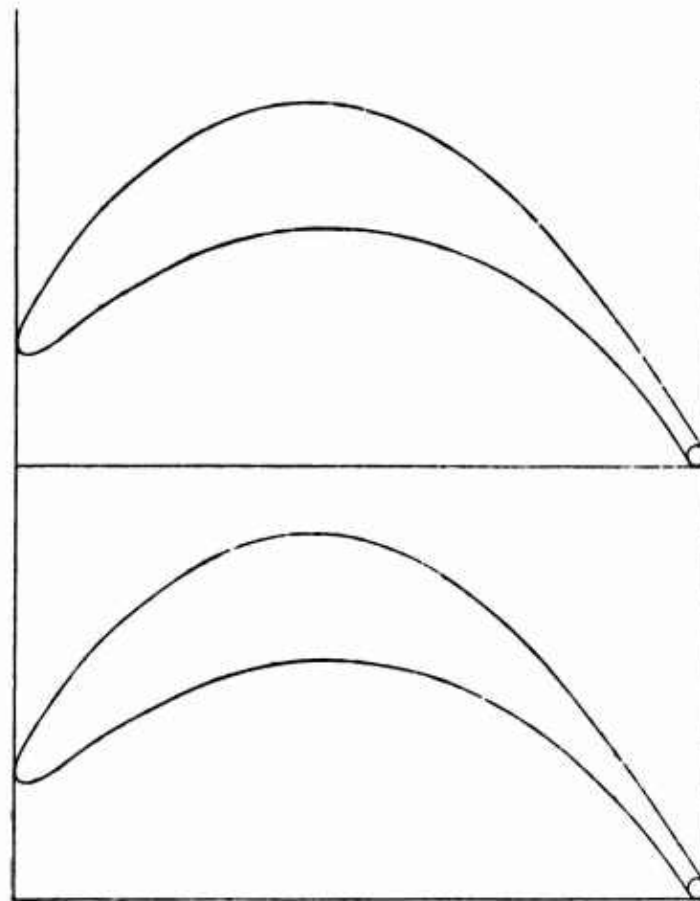
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Figure 26. Nozzle Profile Family II



Scale 4:1

Figure 27. Nozzle Profile Family III



Scale 4:1

Figure 28. Bucket Profile

TABLE V

Comparison of X376 to X353-5 Buckets

	<u>X376</u>	<u>X353-5</u>
Length/pitch diameter	.0363	.0531
Aspect ratio	1.77	2.64
Solidity	1.65	2.08
$t/(t + d_o)$	.067	.100
Turning angle	111°	116°
Unguided turning	10.6°	16.3°
Zweiffel loading parameter	.932	.756



The exit stator vanes are identical to the X353-5 turbine stator vanes except that the trailing edges of the pitch fan are thinner because of the use of thinner material in manufacture. Also, the orientation angle has been increased because of the increased rotor exit swirl angle. The exit stator profile is shown on Figure 29 and is defined by the following aerodynamic parameters:

Camber Angle	13°
Orientation Angle	6.5°
Thickness Distribution	NACA 65-012 (Except for leading edge modification)
Chord	1.5 inches
Maximum Thickness	12%
Trailing Edge Thickness	.037 inches
Angular Spacing	6.925°
Solidity at Mid-Span	.630
Mean Camber Line	Circle Arc

#### Off Design Performance

Figure 30 depicts the predicted turbine off-design performance map. The energy and efficiency values shown on this figure do not account for partial admission or leadage losses. The actual shaft power and efficiency may be computed by reducing the map values according to the following equations:

$$HP = 1.370 W_g \Delta h - \delta_{am} \left[ 2.35 \left( \frac{N}{10^3} \right) + .473 (1-F) \left( \frac{N}{10^3} \right)^3 \right]$$

$$\eta_{TT} = \eta_{map} \left( .969 - \frac{.707 \delta_{am}}{W_g \Delta h} \left[ 2.35 \left( \frac{N}{10^3} \right) + .473 (1-F) \left( \frac{N}{10^3} \right)^3 \right] \right)$$

where:  $\eta_{TT}$  = turbine impact efficiency based on the axial component of leaving velocity

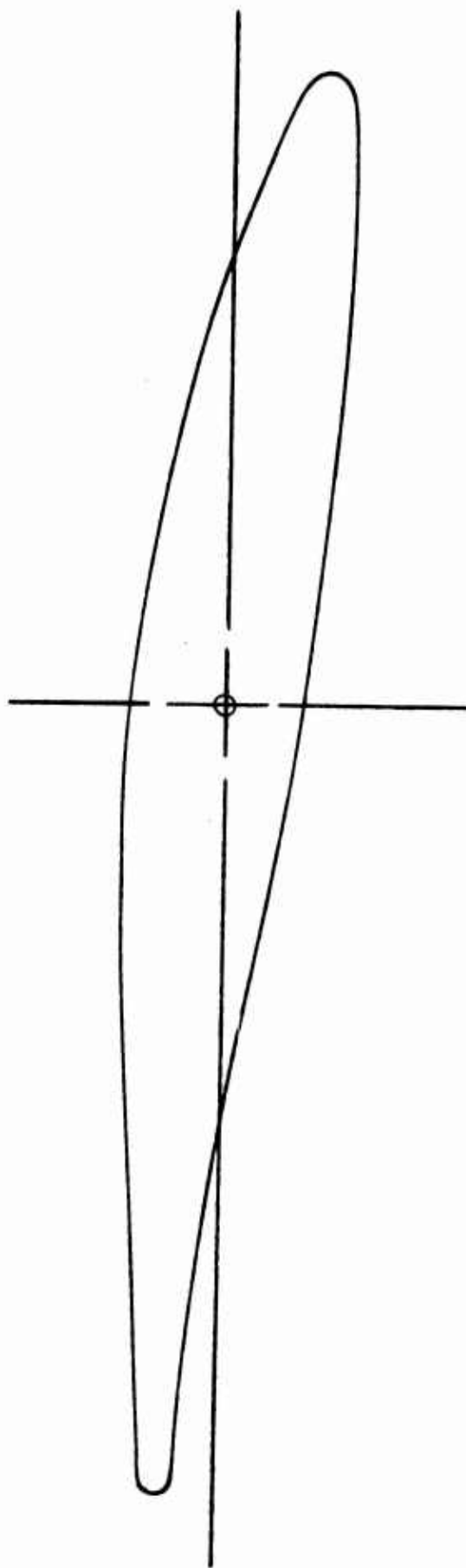


Figure 29. Exit Stator Vane Profile

**NOTE:**

1) MAP DOES NOT INCLUDE PARTIAL ADMISSION LOSSES.

2) EFFICIENCY IS TOTAL TO TOTAL BASED ON AXIAL DISCHARGE CONDITIONS.

$$3) \text{ H.P. SHAFT } = 1.370 W_{15.4} \Delta h_{\text{MAP}} - \delta_{\text{amb}} \left[ 2.35 \left( \frac{N}{10^3} \right) + .473(1-F) \left( \frac{N}{10^3} \right)^3 \right]$$

4)  DENOTES DESIGN POINT.

5) F = FRACTION OF ADMISSION ARC.

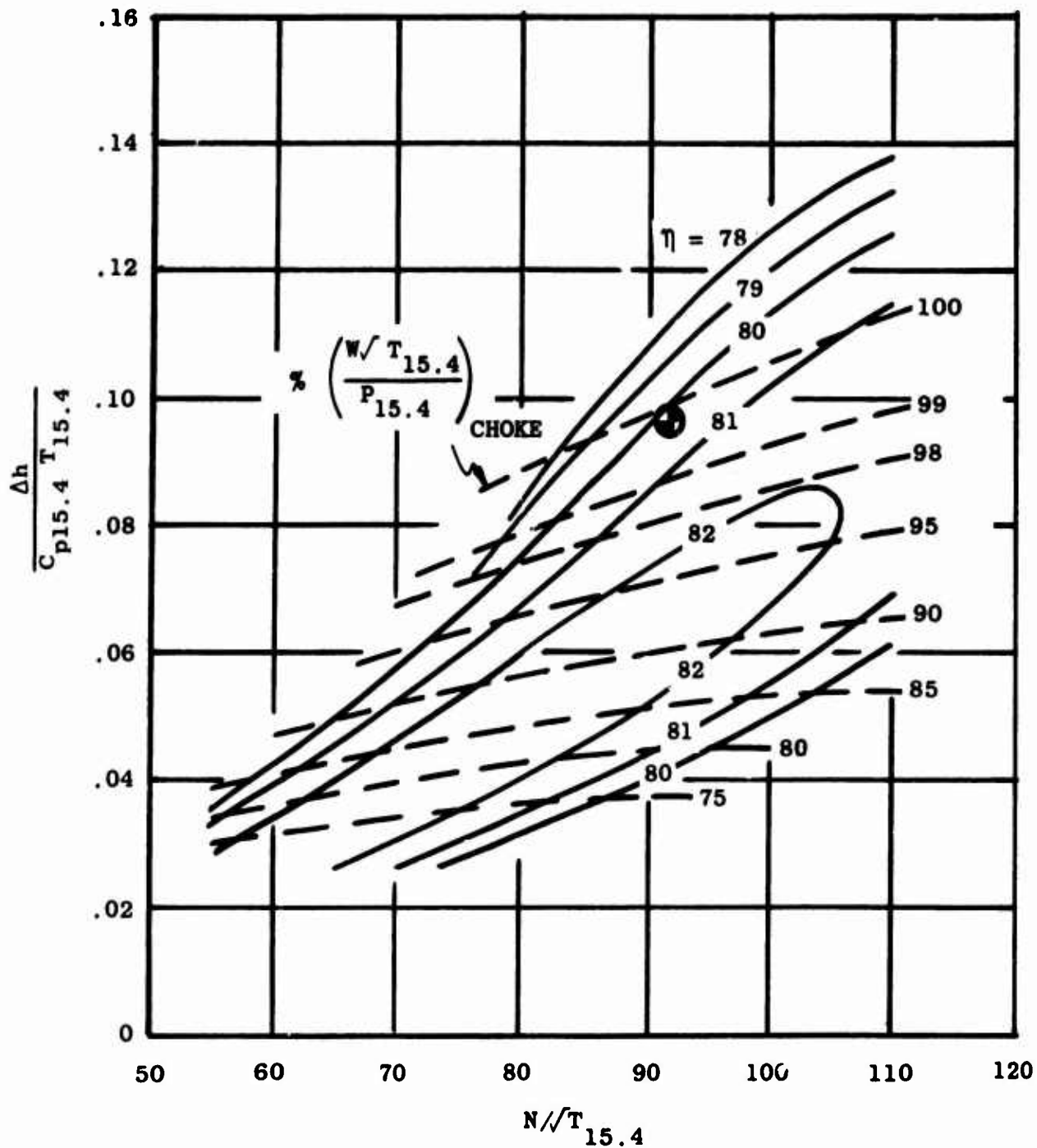


Figure 30. X376 Turbine Map

$\eta_{\text{map}}$  = map value of efficiency  
 $\delta_{\text{am}}$  = ambient pressure/14.7  
 $W_g$  = turbine inlet flow, pounds/second  
 $\Delta h$  = map value of turbine energy, BTU/pound  
 $\text{HP}$  = net horsepower output of turbine  
 $N$  = rotational speed, RPM  
 $F$  = admission arc as fraction of  $360^\circ$ .

## 2. MECHANICAL DESIGN

Figure 31 is a cross section showing the major components of the X376 pitch fan; front frame, rotor, rear frame, and scroll.

### a. Rotor

#### General

The X376 fan rotor is a single stage axial flow design similar to the X353-5B lift fan. Design philosophy on the two rotors is basically the same. This report will discuss design features of the X376 fan and deal with criteria only when it deviates from the X353-5B rotor.

#### Design Objectives

1. Fan aerodynamics scaled down from the X353-5B fan
2. Fan radius ratio = 0.45
3. Rotor speed

100% speed	4074 RPM
Maximum continuous speed	4481 RPM
Maximum short time overspeed	4684 RPM

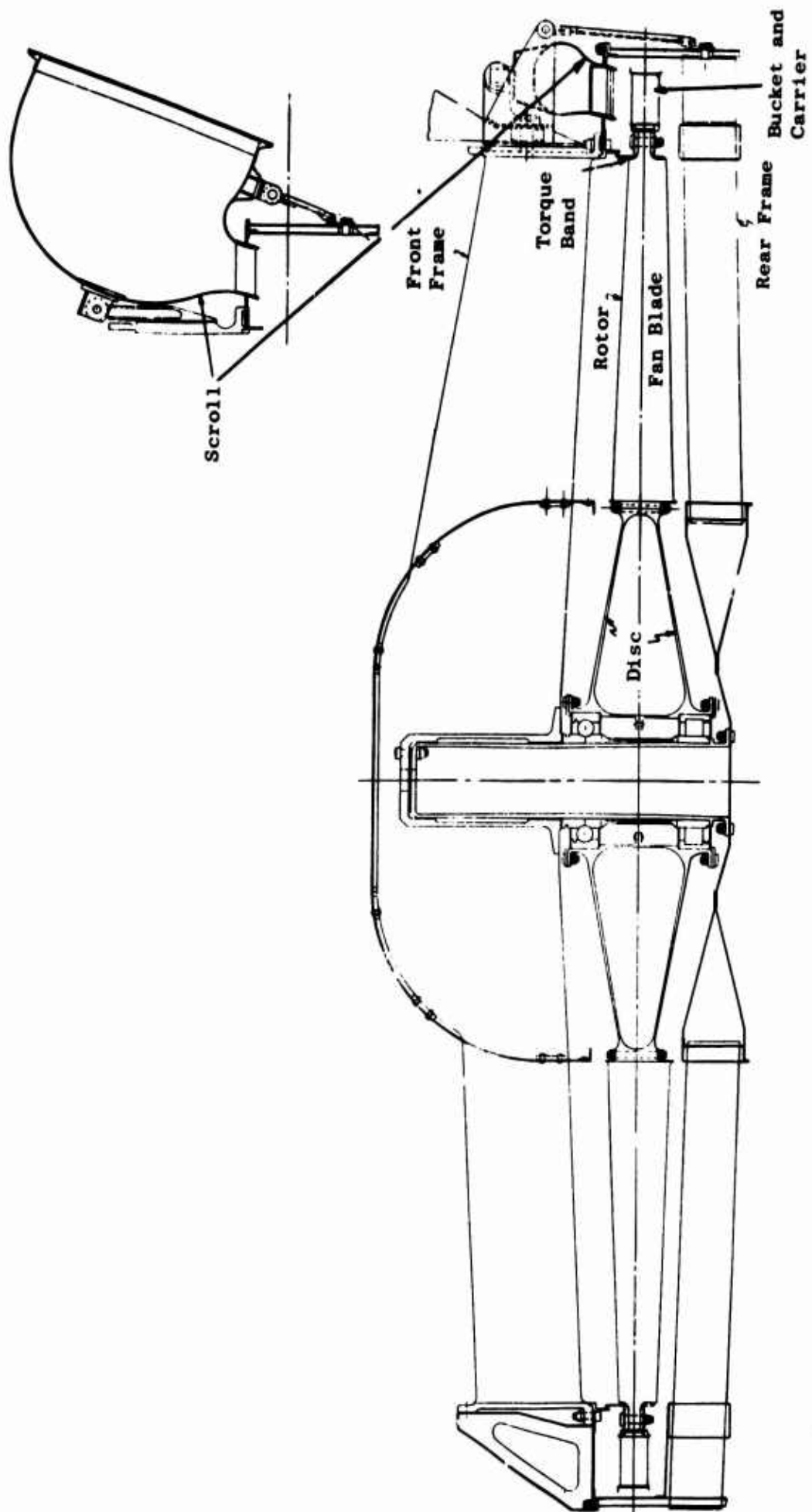


Figure 31. Pitch Fan Cross Section

### Turbine Sector Design

The pitch fan turbine sector is a brazed fabricated structure manufactured from Inconel X material. This component consists of 252 buckets uniformly distributed over 18 carrier segments. A single segment is shown in Figure 32.

Several major differences exist with the pitch fan turbine sectors in respect to the X353-5B design. An 0.008 inch bucket material thickness was utilized rather than 0.015 inch. The heavier material was selected for the X353-5 fan based upon erosion and impact damage criteria. After several hundred test hours of experience, a more accurate appraisal of erosion and impact damage considerations was possible, thus the 0.008 inch material was selected for the X376 design.

The scaling of the X353-5B fan to the X376 size plus the reduction in solidity, produced a short stubby bucket. The need for a longitudinal rib was based entirely on panel vibration criteria. With the X353-5B as a base, calculations were performed to establish a vibration index for the X376 design. Bench tests of bucket cascades were made under high velocity air and varying bucket incidence angles. Since no bucket panel vibration problems were evidenced, the longitudinal rib was eliminated.

Since the entire X376 turbine sector is a fabricated sheet metal structure, an increase in bending stress inertia was realized by the addition of the blade tip seal.

The tangentially oriented pin used on the X353-5B was changed to an axially oriented bolt for the X376. Ease of assembly and elimination of interaction with carrier radial bending were the prime reasons for this design.

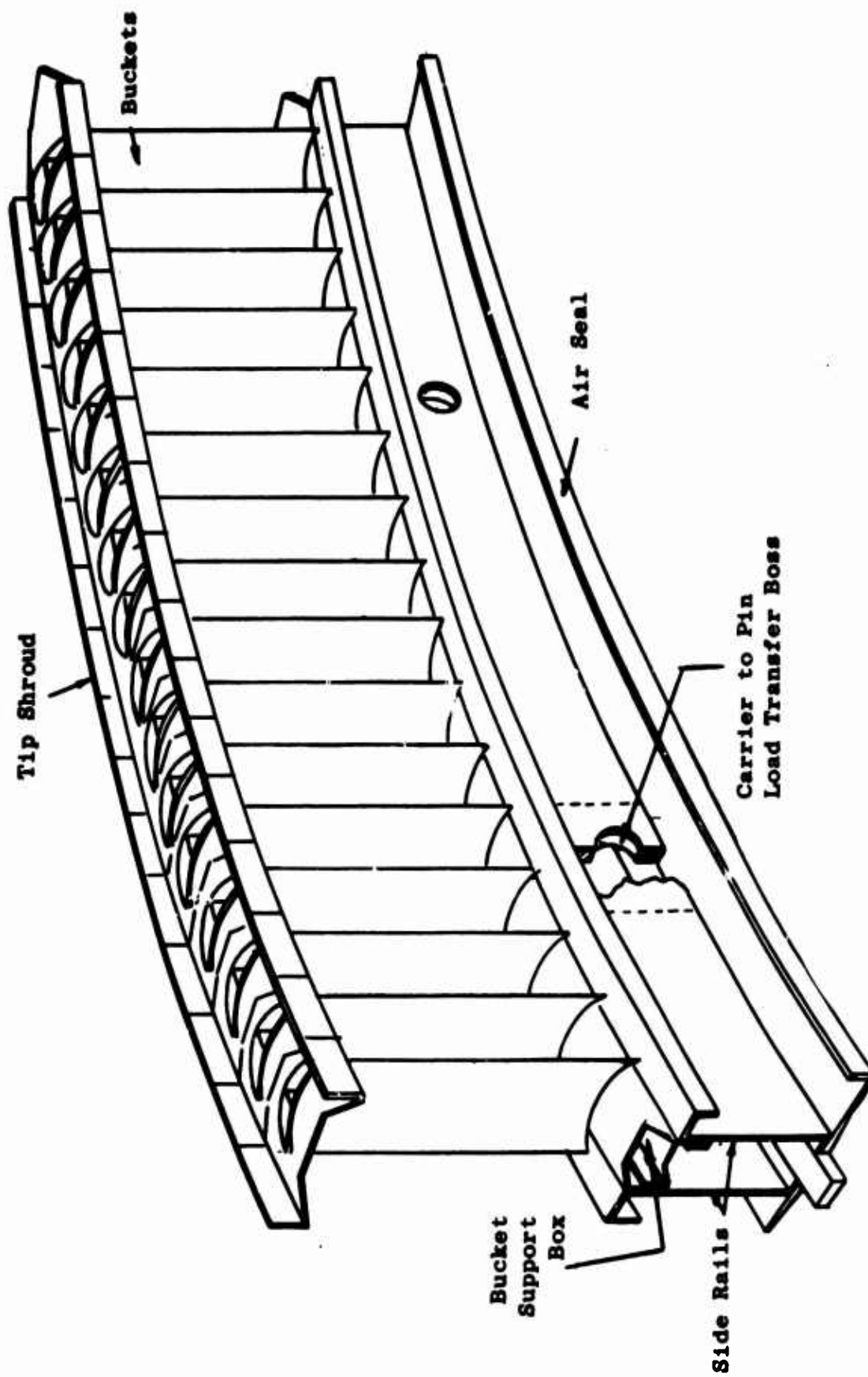


Figure 32. Pitch Fan Bucket & Carrier Assembly

## Fan Blades

The fan blades were manufactured from 7AL 4MO titanium bars for light weight. The blades deviate from the constant section X353-5B design as a means of optimization based upon stress distribution, flexural frequency, Cosine 2 $\theta$  stresses, and low airfoil edge stress for minimum effect from foreign object damage.

Stresses in the tang are based upon stress concentration factors for steady state loads, bearing loads, and tearout stress. Tang stress levels were held within General Electric experience for pinned clevis design.

Blade attachment to the disc is effected through the use of a single hook dovetail. This dovetail form is an exact scale from the X353-5B form. Analysis of the dovetail stress has shown that the design is as strong or stronger than the airfoil for the following vibratory modes and rotor speeds:

Blade first flexure	4684 RPM
Blade second flexure	4684 RPM
Blade first torsion	4684 RPM
Gyroscopic maneuver loads (2 rads/sec)	4074 RPM
Cosine 2 $\theta$	5100 RPM

Prior to assembly, the blade tip tang and dovetail were shot peened and coated with a graphite-resin compound to resist fretting in titanium applications.

Figure 33 reflects an analysis of the pitch fan blade vibration frequencies and the proximity of these frequencies to the per rev stimuli across the rotor operating speed range.



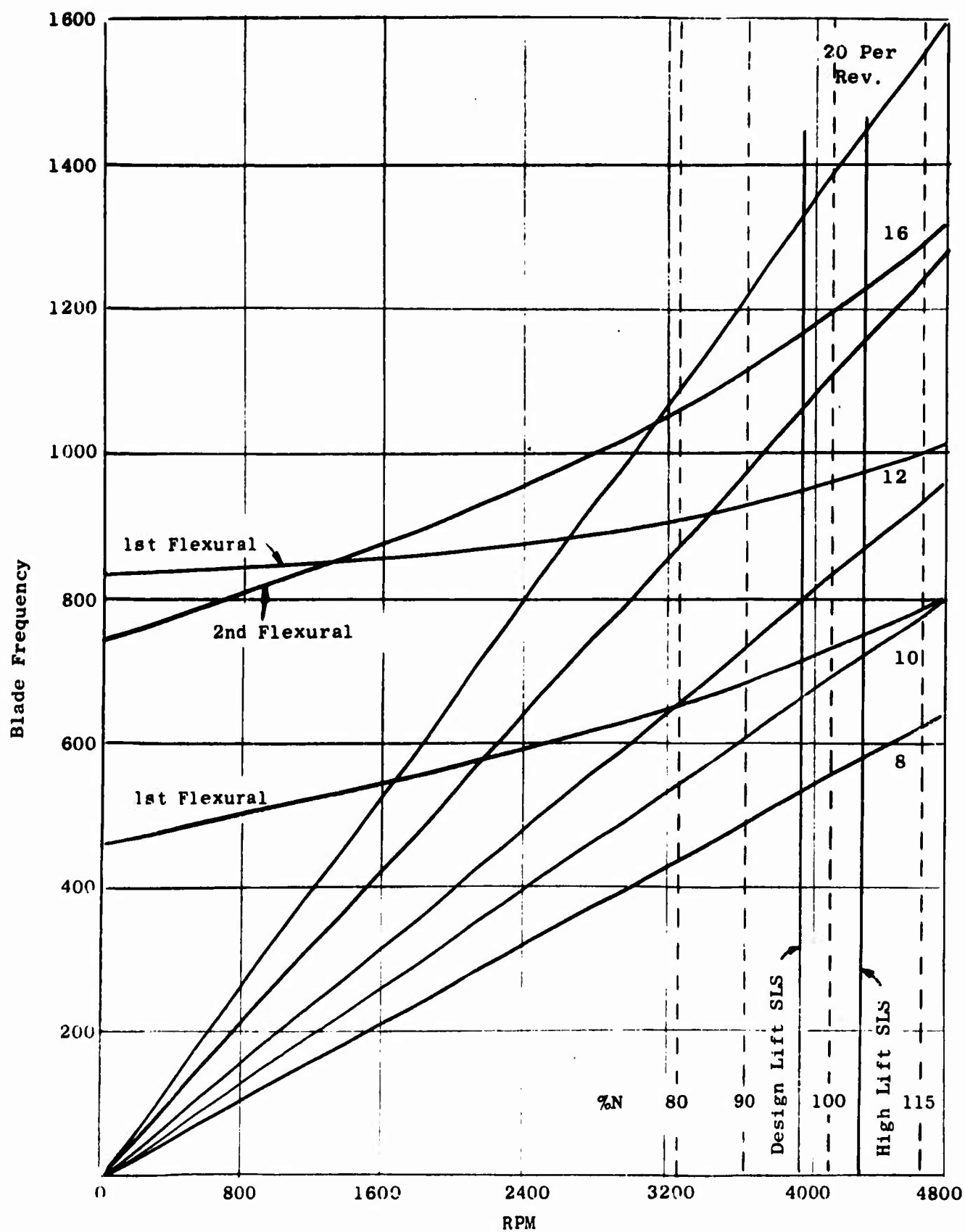


Figure 33. Pitch Fan Vibration Analysis

## Disc

A double conical disc design similar to that used in the X353-5 design was selected for the X376 fan. The major difference between the two designs is that in the X376 fan the bearings are placed at the center of the disc rather than on a shaft on which the disc is shrunk. This type of construction was selected for the X376 to reduce the overall weight of the fan, as material that would be required in the front frame to assure correct bearing assembly is eliminated. The disc spring stiffness is increased by this design, and raises the rotor cosine  $2\theta$  mode frequency above the operating speed range. In addition to the use of steel body-bound dowels at the rim to eliminate axial rim separation, the X376 disc halves are bolted together between the bearings at the disc hub. Figure 34 is a stress deflection diagram for the X376 disc under steady state loading at maximum continuous design speed.

## Torque Transmission

The torque transmission between the active and inactive sections of the fan is accomplished by a single-piece ( $360^\circ$ ) torque band as shown on Figure 35. The shear load is transmitted into and out of each carrier by a grommet carried by the band and bolted to the integral seal portion of the carrier. The maximum load carried by the band occurs at startup, and results in a stress of 41,700 psi which is within the allowable vibratory stresses of the R41 material from which the band is manufactured. Radial bolts are used to attach the band to the ends of the carrier, thus eliminating band buckling and providing an emergency torque transmitting means between adjacent carriers. Oversize holes in the band at these locations are included to permit carrier thermal expansion without loading the band.

Bore Temperature Rise	0°F	200°F
Bore Radial Deflection Avg.	.0026 in.	.0047 in.
Rim Radial Deflection Avg.	.0082 in.	.0099 in.
Blade Load - 5550 lb/Blade		
Speed - 4684 RPM		
Material Allowable Stress - 130,000 psi		

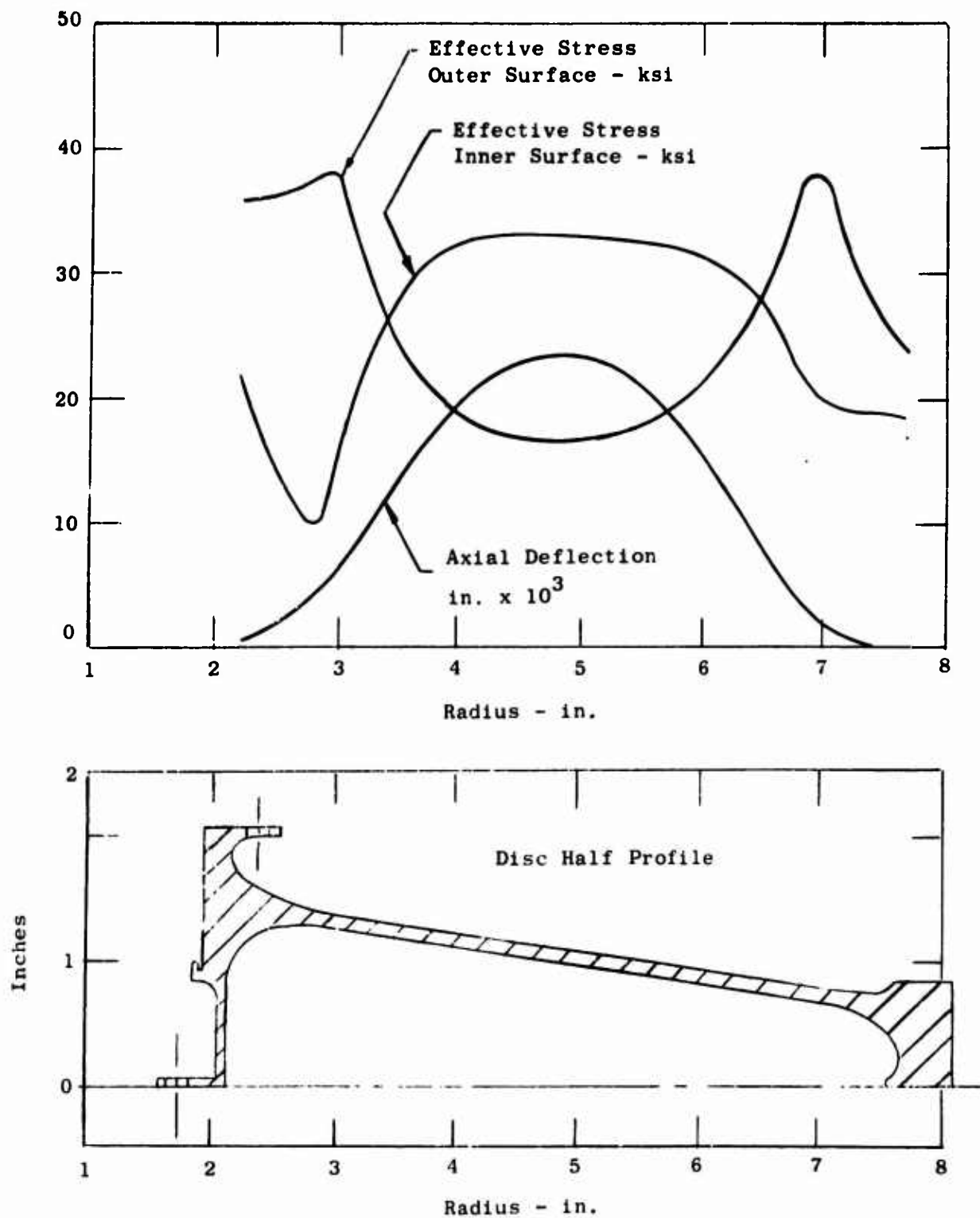


Figure 34. Disc Stress and Deflection

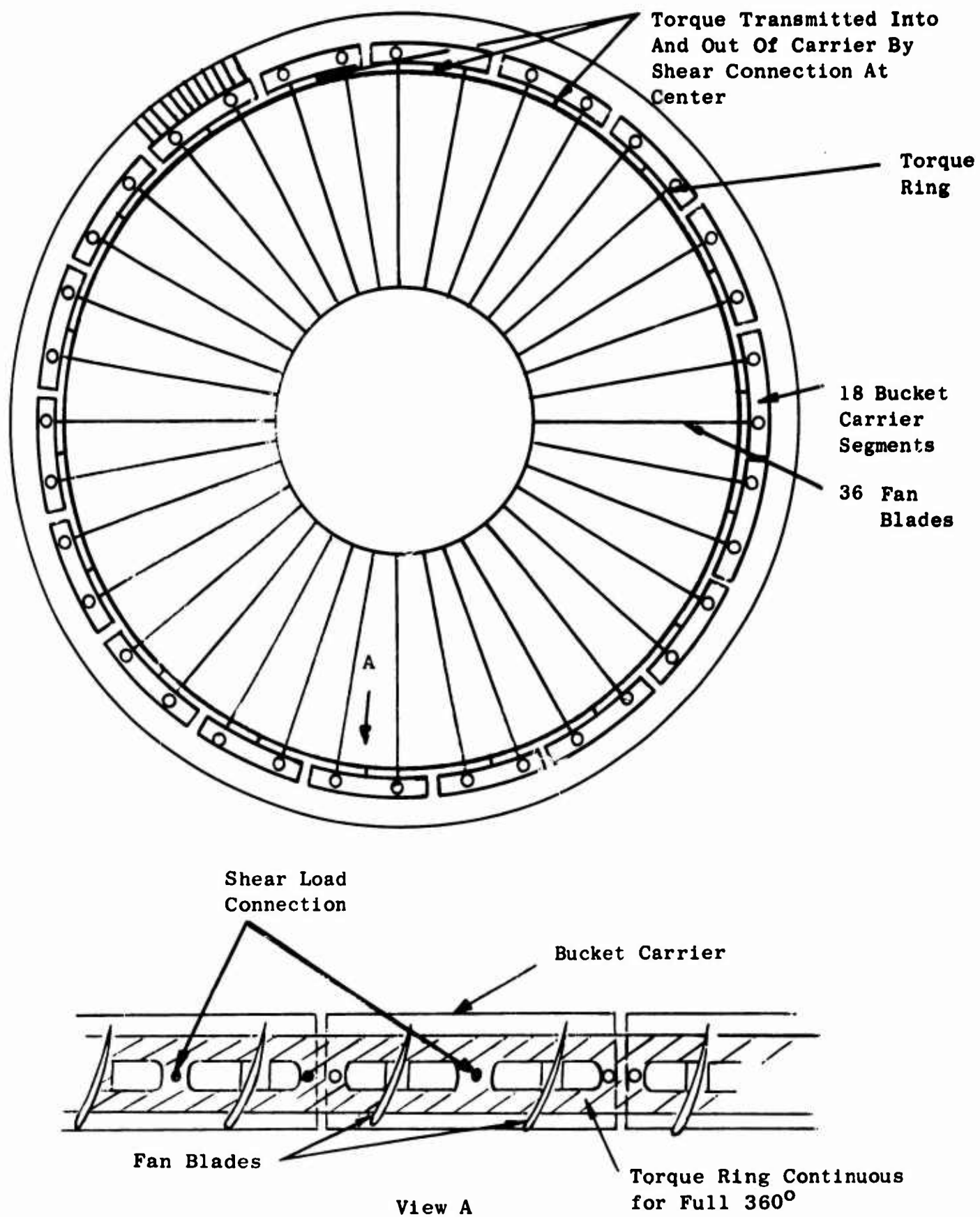


Figure 35. Pitch Fan Torque Band

### Blade Platform

The X376 dovetail form is sized to contain the airfoil without a blade shank. This design eliminates the need of a blade platform component to form the flow path at the blade root as in the X353-5B design.

### Bearings and Grease Shields

The bearing system used on the X376 is the same as that used in the X353-5 design except that the bearings are placed at the center of the disc and the outer races rotate. A cross-section through the hub is given on Figure 36. The bearings are grease lubricated using the same unitemp 500 high temperature grease that has been successfully used on the X353-5 testing.

### b. Frames

#### Front Frame

The X376 front frame, which is shown diagrammatically on Figure 37 is designed to carry the following loads:

1. Rotor lift load, gyro and partial admission loads
2. Rear frame lift loads and tangential loads
3. Scroll loads.

The frame is a cast magnesium structure with eight radial struts supporting an outside diameter casing and a hub at the center. Magnesium was chosen for weight considerations. An eight strut design was selected based upon increased stability of the frame outer ring during casting and operation as well as the need to accept scroll loads in between the mounting points. The casting is galvanically anodized to prevent corrosion. Insulation material is assembled between the "hot" scroll mounts and the casting to insure that overheating does not become a problem. Mounts are located on the outside diameter of the frame in line with the struts at the 90°, 180°, and 270° locations.

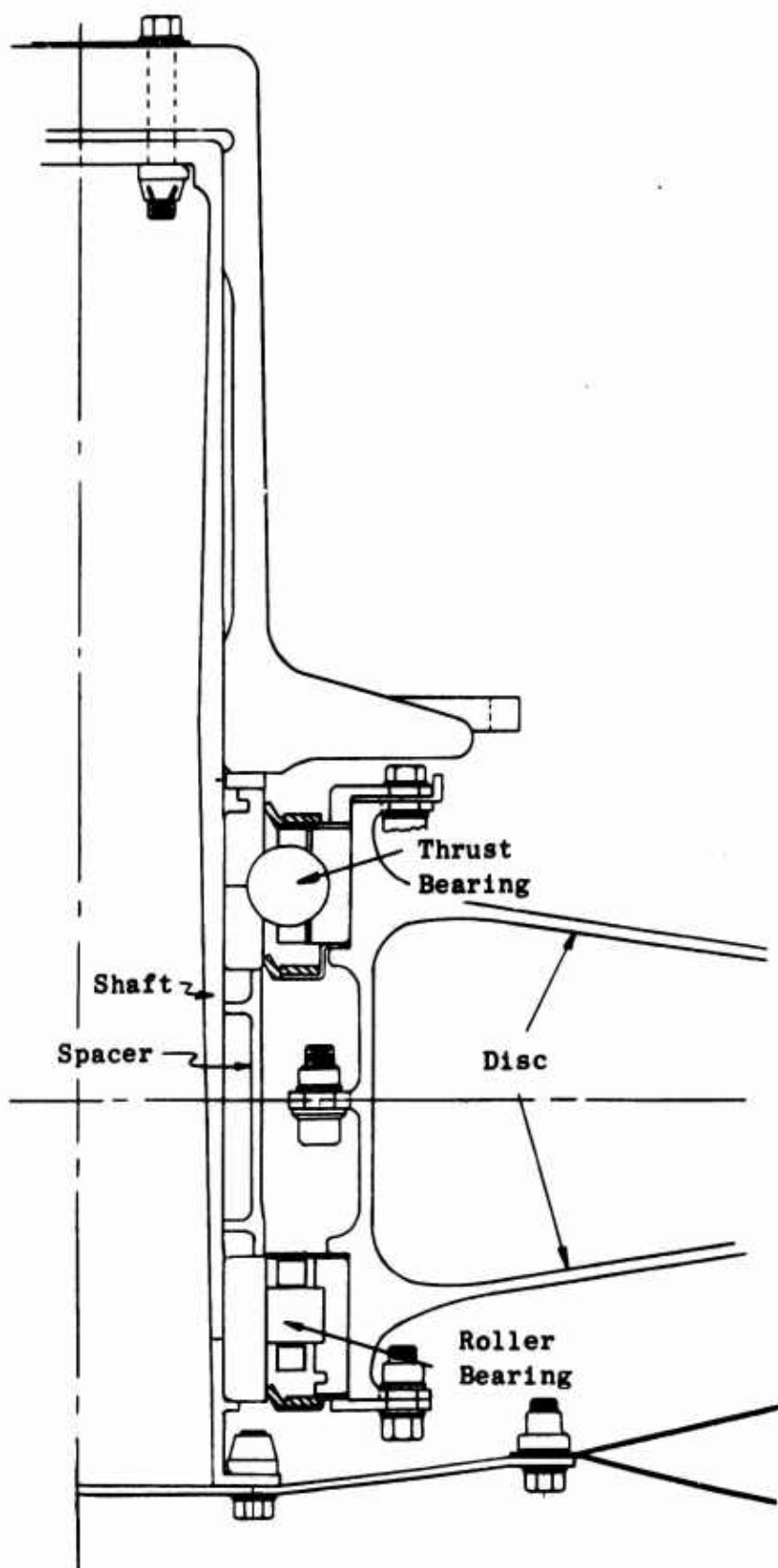


Figure 36. Hub Cross Section

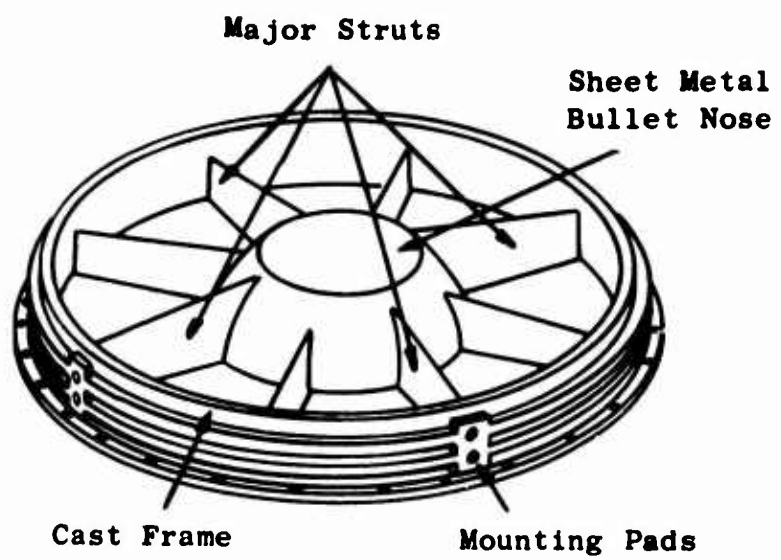


Figure 37. Front Frame

## Rear Frame

The rear frame of the X376 fan, as shown in Figure 38, is a 42.6 inch diameter wheel-type structure having 52 stator blades and is similar in design to the X353-5. The rear frame is flange-supported in the inactive turbine arc to the front frame and to the scroll in the active turbine arc by three A-frame hangers. Structurally the frame was sized to carry both tangential and axial air loads, the former having the largest influence since this load acts about the stator vane minor axis. The frame is fabricated from 0.010 Inconel X material utilizing the same braze alloy and techniques successfully developed for the X353-5 rear frame.

Thermal stress in the rear frame is controlled by axial slots in the outer casing and sealed with a channel stiffener section which is welded over the slot. Thermal growth takes place tangentially rather than radially.

Stator frequencies were computed and are shown on the Campbell diagram, Figure 39. Design of the stator vanes was such that X353-5 tooling was utilized for X376 fabrication even though the stock thickness of the X376 vanes is 0.010 instead of 0.020.

A sandwich type insulation blanket having 0.0015 stainless steel skins is formed over the outer diameter of the turbine casing to reduce heat transfer to the airframe.

### c. Scroll

Although the same design principles that were used for the X353-5 scroll were employed for the X376 component, space limitations for a fuselage installation allowed for a much simpler design. This installation allows the X353-5 "gooseneck" to be eliminated as well as removal of the torque tubes.



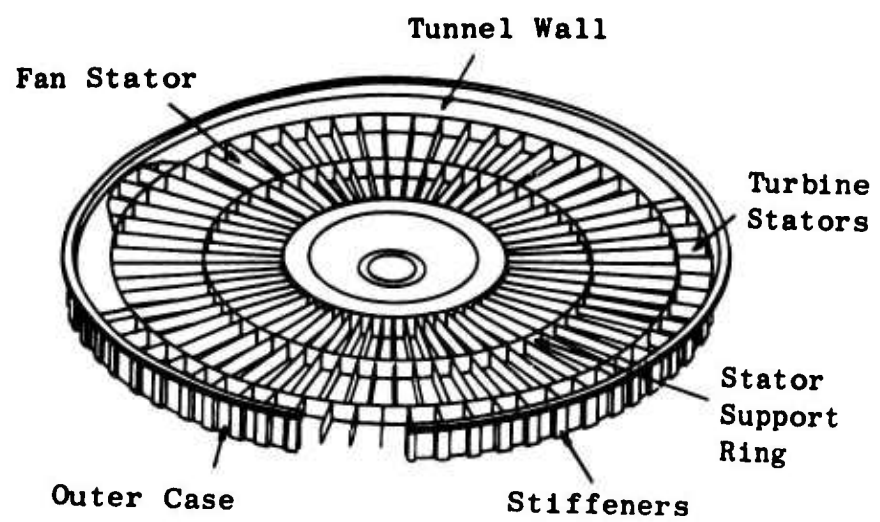


Figure 38. Rear Frame, Pitch Fan

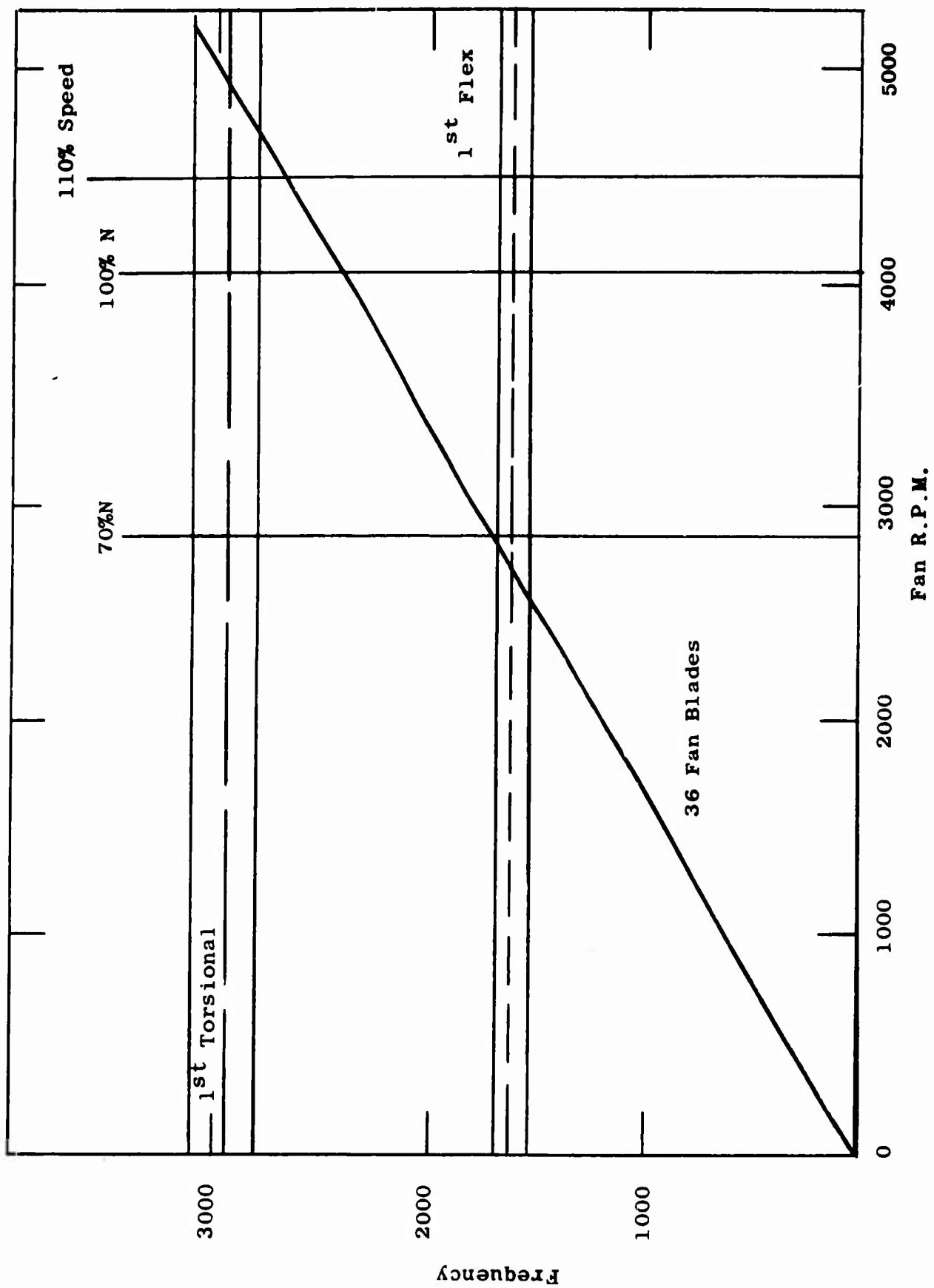


Figure 39. Stator Frequencies

The design philosophy was to minimize internal pressure stresses by making the scroll skins circular arcs and to provide mechanical ties at the intersection of the nozzle box to the scroll duct. These mechanical ties are airfoil-shaped struts which are aligned with the flow for minimum internal loss and located as shown in Figure 40. Apart from the pressure loads, the scroll is also sized to carry both the nozzle reaction and the scroll inlet piston force loads. The bending and torsion moment distributions along the arms for these conditions are shown on Figure 41 and the resultant stresses (based on the section remaining circular) are shown on Figure 42.

The main body of the scroll and the stiffener hat sections are constructed from 0.015 inch thick sheet material with the nozzle partitions and struts machined from solid bar material. The solid airfoils were chosen in preference to a fabricated hollow design in order to reduce the cost of this component with only a slight weight penalty. Although the scroll skins and hat sections are joined together by welding, the nozzle partitions and struts are brazed into eloxed slots in the main structure. This brazed nozzle design eliminates the flowpath distortion resulting from weld shrinkage plus affords greater dimensional stability. The material selected for this component is Hastelloy X. The mechanical and metallurgical properties displayed by this material are particularly suited to the formability and weldability requirements of the manufacturing cycle and to the extended endurance under stress required in the elevated temperatures encountered during operation.

To fulfill the cross ducting requirements of the XV-5A airplane, two identical 90° scrolls are provided on the X376 fan. Each scroll has its own mounting system and is attached to the front frame in a similar manner to the X353-5 scroll. The centers of the scrolls are fixed and the two arms are allowed to grow tangentially and radially along a pin at each end that is supported by a mount which is attached to the front frame, Figure 43.

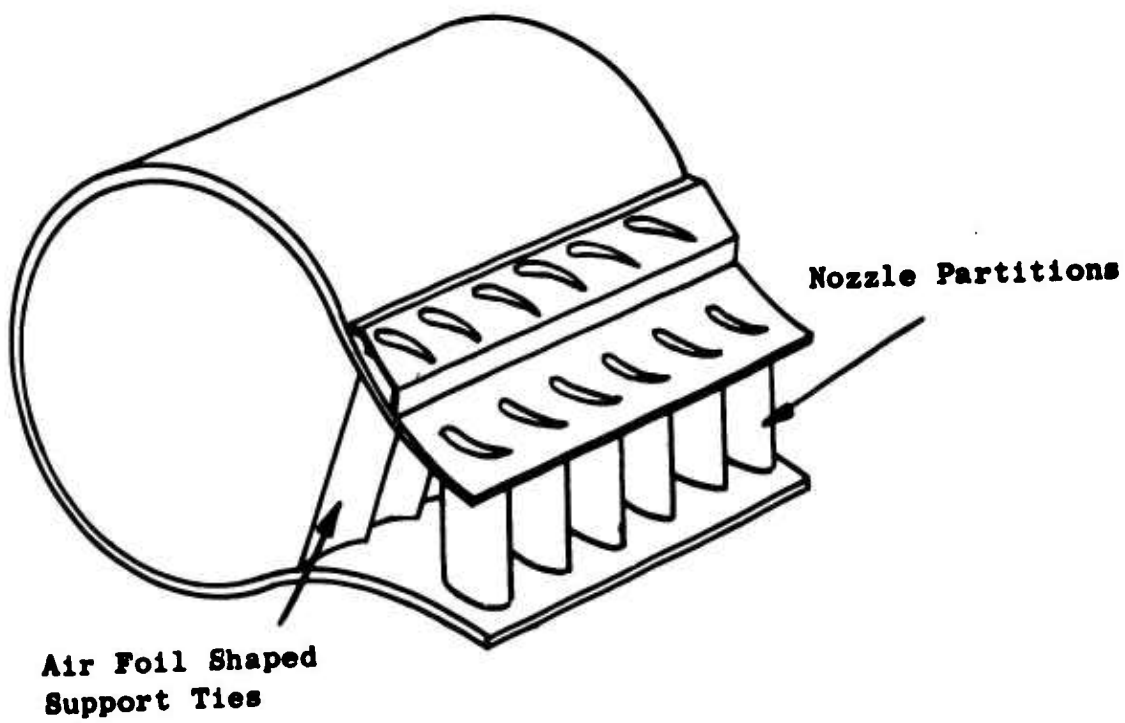


Figure 40. Circular Section Ties

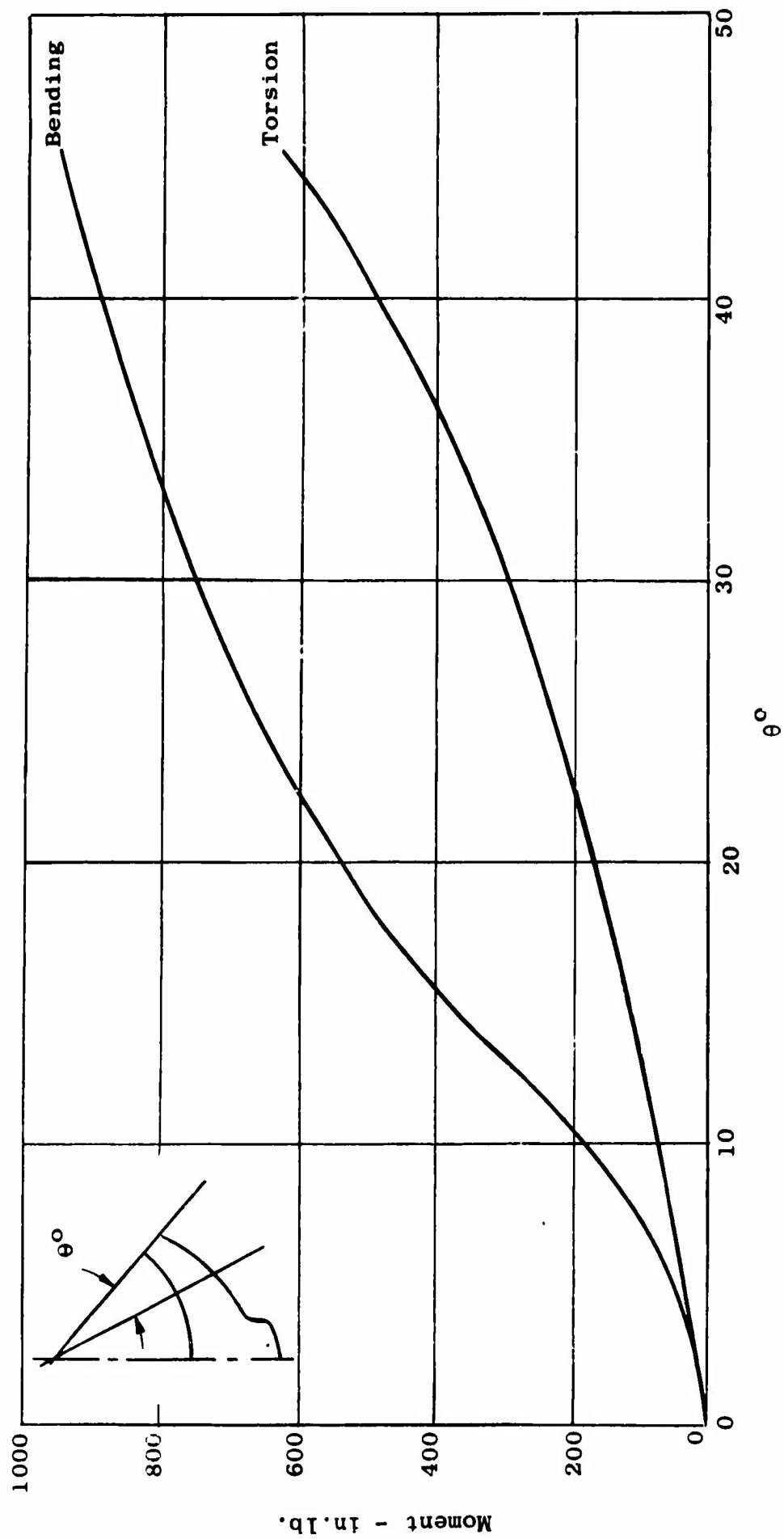


Figure 41. Pitch Fan Scroll and Bending Torsion Moment Distribution

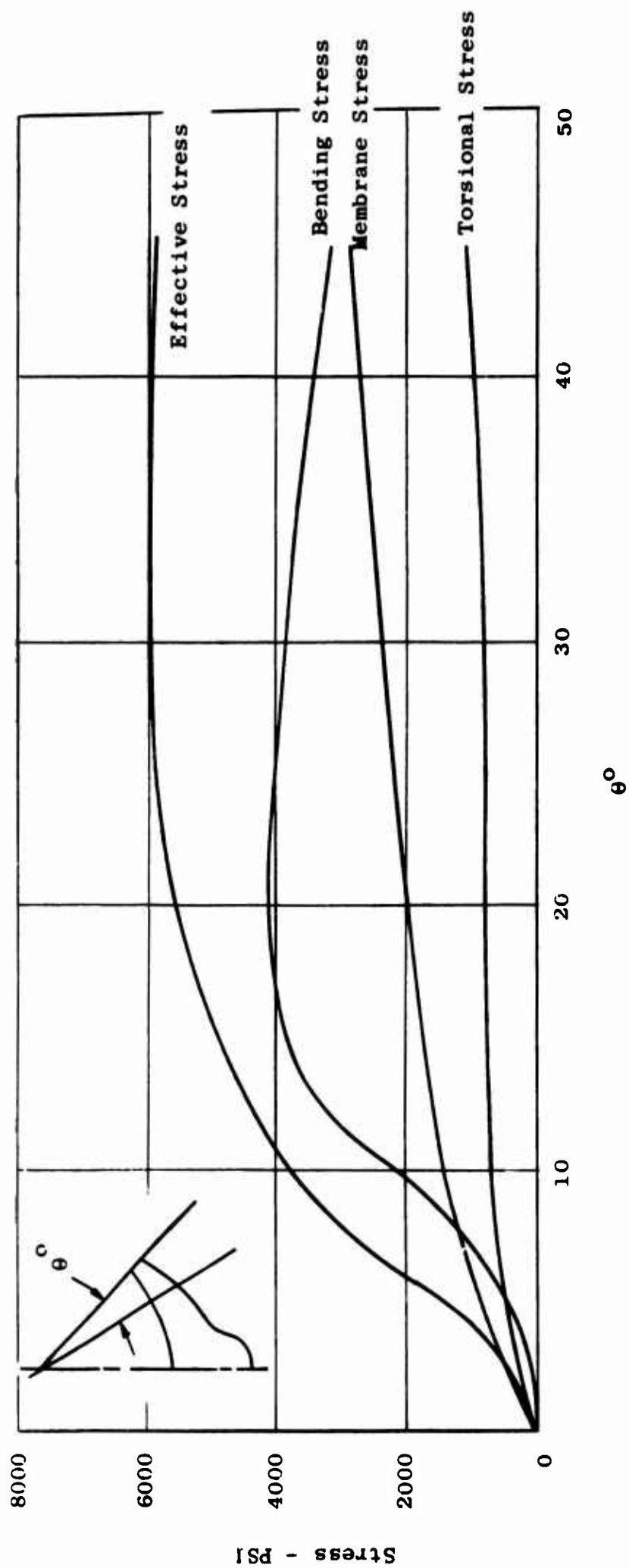


Figure 42. Pitch Fan Scroll Stress Distribution

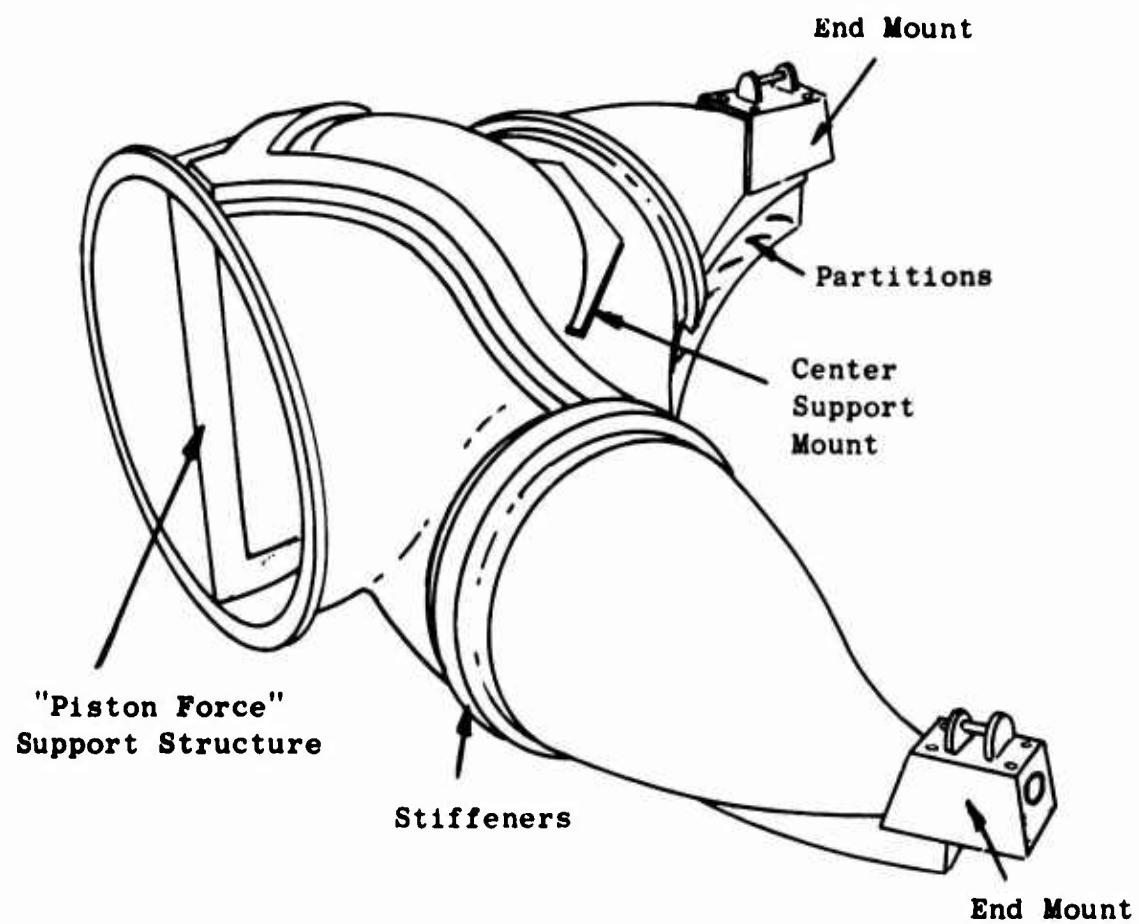


Figure 43. Pitch Fan Scroll

The scrolls are designed to accept a maximum of 14% of the discharge from a J85-5 basic jet engine. For power settings less than maximum, a trim adjustment is provided by means of "blocker plates" which are inserted through the inlets and down the scroll arms to the desired position. Two adjustment positions are provided in each scroll arm.

### C. DIVERTER VALVE

Only minor changes to the diverter valves were necessary to adapt it to the XV-5A airplane. The basic change from the original configuration is a five (5) degree cut-off angle on the diverted discharge leg. This change was incorporated to preserve interchangeability between the cross duct assemblies with the J85 turbojets installed at a 5° nose-up attitude.

Exit flanges on both the straight through and diverted legs were changed from a bolted design to a quick disconnect design in order to match the mating duct flanges and to simplify assembly. Although a slightly larger flange was required than originally planned due to the apex bend radius on the mating ducting formed flange, the addition of a relief groove in the flange face allowed this change be made without any increase in weight. The added relief groove was fully evaluated to insure that no loss of joint efficiency or seal effectiveness existed.

A comparison between the material properties of L605, the previous material, and Hastelloy X showed that the latter material could be directly substituted for the doors and valve body without impairing the structural integrity of the diverter valve. The major advantage of this change was the 10% lower density of Hastelloy X allowed a considerable weight saving.

Door position indicator switches were added to provide interlock functions to the aircraft electrical conversion system. Two switches per valve were provided, one to indicate the straight through position and the other for the diverted position.



A tandem hydraulic actuator was designed which replaced the single piston original design. From an overall reliability standpoint, a dual hydraulic piston actuator was chosen which completely separates the aircraft's primary and secondary hydraulic systems.

A mechanical coupling was included in the diverter valve design to cross-connect the two diverter valves in the XV-5A application. It was required that the coupling transmit the full driving torque of the hydraulic system as well as absorb misalignment between the valves. The design consisted of a modified straight door bushing having four slots, and a telescoping coupling having four teeth as a driving connection. No changes were necessary to either the door or valve body, and the coupling can be assembled without removal of the valves from the aircraft.

#### D. J85 FIREWALLS

To provide a fire seal separating the forward and aft portions of each engine, a firewall was designed and fabricated unique to the J85 engines, but generally similar to firewalls on the CJ-610 engines. The firewall seals surround the engine casing one inch aft of the combustor forward flange. All fuel and oil connections, as well as all engine accessories, are on the forward side, eliminating the possibility of a fire caused by fuel contacting the hot combustor or turbine casings. The net increase in engine weight with the firewall replacing the conventional insulation blanket is 3.8 pounds per engine.

The firewall, tailored to the XV-5A design, mates with an airframe-supplied firewall-to-fuselage seal, and is constructed of titanium alloy.

## I V. C O N T R O L S

### A. X353-5B RPM INDICATING AND LIMITING SYSTEM

The system provides cockpit read-out of rpm from the XV-5A's three fans, rpm recording signals for the P.C.M. flight recorder, top speed pilot warning, overspeed power cut-back, and test functions.

The electronics component of the system is shown in Figures 44 and 45. Mechanically the component consists of a stack of fiberglass-gold printed circuit boards encircled in urethane foam support, an access panel for calibration and installation adjustment, associated electrical connectors, shock mounts, and dust/moisture seals. The component is mounted within the XV-5A avionics bay; cables were supplied as an integral part of the XV-5A electrical system.

Electrically, the component consists of solid state devices including signal transistors, power transistors, signal diodes, power diodes, regulating diodes and a controlled rectifier. Except for power devices, all circuit components are mounted on a series of eight printed circuit boards. Power devices are attached to  $\frac{1}{4}$  inch aluminum case structure to provide heat dissipation. Functionally, the circuit boards include:

1. Pickup frequency - to - D.C. voltage converter: nose fan
2. Pickup frequency - to - D.C. voltage converter: No. 1 fan
3. Pickup frequency - to - D.C. voltage converter: No. 2 fan
4. Dual channel trip point detector: nose fan

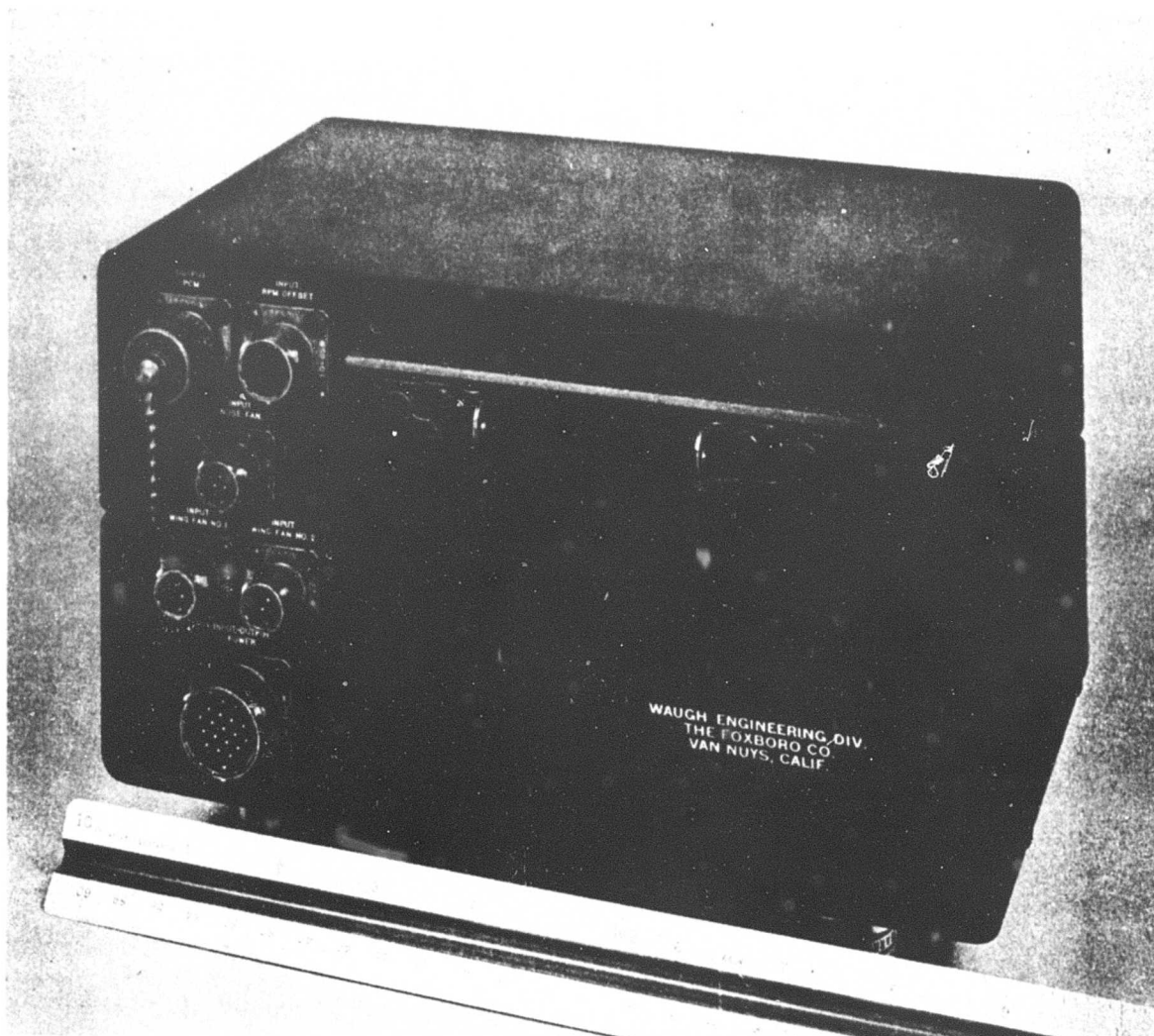


Figure 44. Electronics Component - RPM Indicating and Limiting System - Exterior View



Figure 45. Electronics Component - RPM Indicating and Limiting System - Interior View

5. Dual channel trip point detector: No. 1 fan
6. Dual channel trip point detector: No. 2 fan
7. Logic and power output
8. D.C. - to - D.C. converter.

Figure 46 is a block diagram illustrating functions of the separate circuit boards; only one of the three channels is shown. A brief explanation of each major function follows.

- a. The frequency - to - D.C. converter amplified the pulse output of fan rpm sensors; sensor frequency is exactly proportional to rotor rpm. A transistor driven saturable reactor integrates signal frequency providing a D.C. voltage proportional to rpm. The D.C. voltage powers a cockpit panel rpm indicator, the trip point circuit, and an alternate analog type flight recorder if needed. Also extracted from the circuit ahead of the integrator is a squared-up high level signal frequency for driving a P.C.M. flight recorder.
- b. The trip point detector compares converter output with precision reference voltages analogous to 100% rpm and maximum permissible overspeed. Detection of either or both conditions is performed and used to drive the logic and power output circuit. Each reference voltage (warning and trip rpm analogy) is adjustable. The circuit also includes an externally controlled offset of the voltage references to provide functional checkout of all system function at less than 100% fan rpm.
- c. The logic and power output circuit accepts cut-back and/or warning signals from the detector to perform warning, cut-back arming, and cut-back action as required.

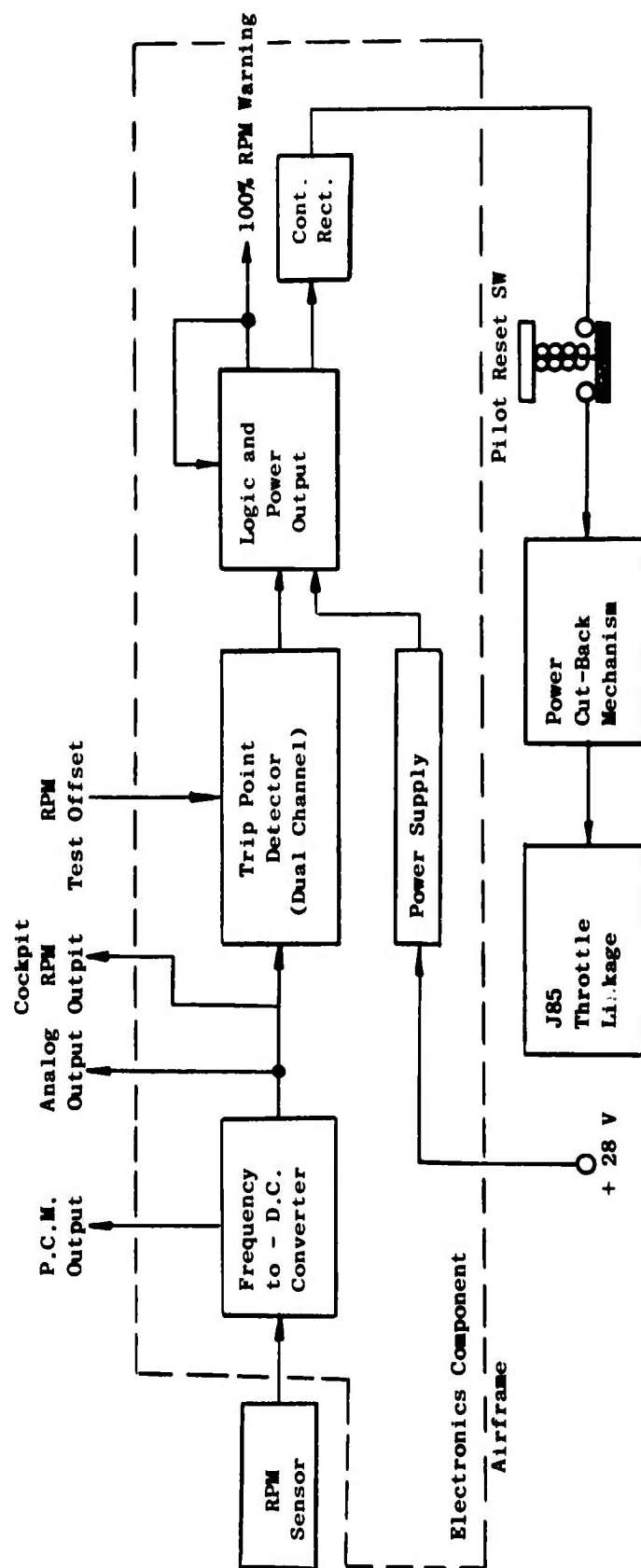


Figure 46. Block Diagram, Circuit Board

- d. The D.C. - to - D.C. Converter is a 28-volt D.C. power supply which isolates the entire component from transient voltage disturbances within the aircraft electrical system. It also provides the precision-regulated reference voltages for the detector circuit.
- e. The controlled rectifier is a high-powered D.C. amplifier/switch which activates the power cut-back components within the J85 throttle linkage mechanism. The pilot retains final authority for resetting full power or disarming the power cut-back function.

## V. M O C K U P S

Mockups of a left hand X353-5B lift fan, a YJ85-5 turbojet engine, a diverter valve, and an X376 pitch fan were provided to the airframe manufacturer to be used as part of the XV-5A aircraft mockup. These mockups, depicted in Figures 47, 48, 49 and 50, included insulation blanket allowance, all mount joints, handling points, customer connections, flange connections, and service points.

Wooden construction was used extensively in all the powerplant components in an effort to attain low cost. The YJ85-5 mockup was obtained as surplus equipment from Northrup Aircraft Company at a considerable cost saving to the Government.



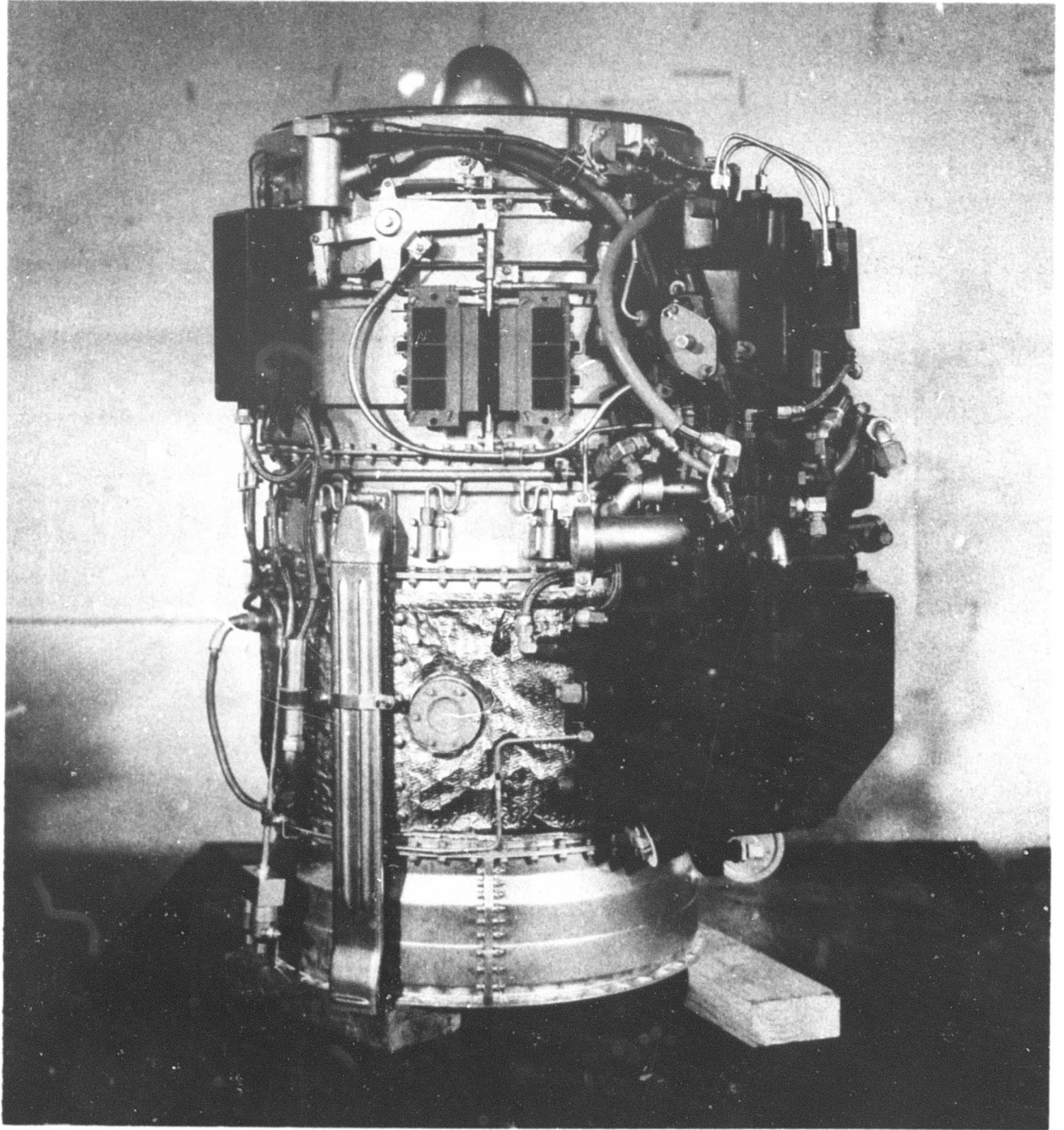


Figure 47. J85 Mockup

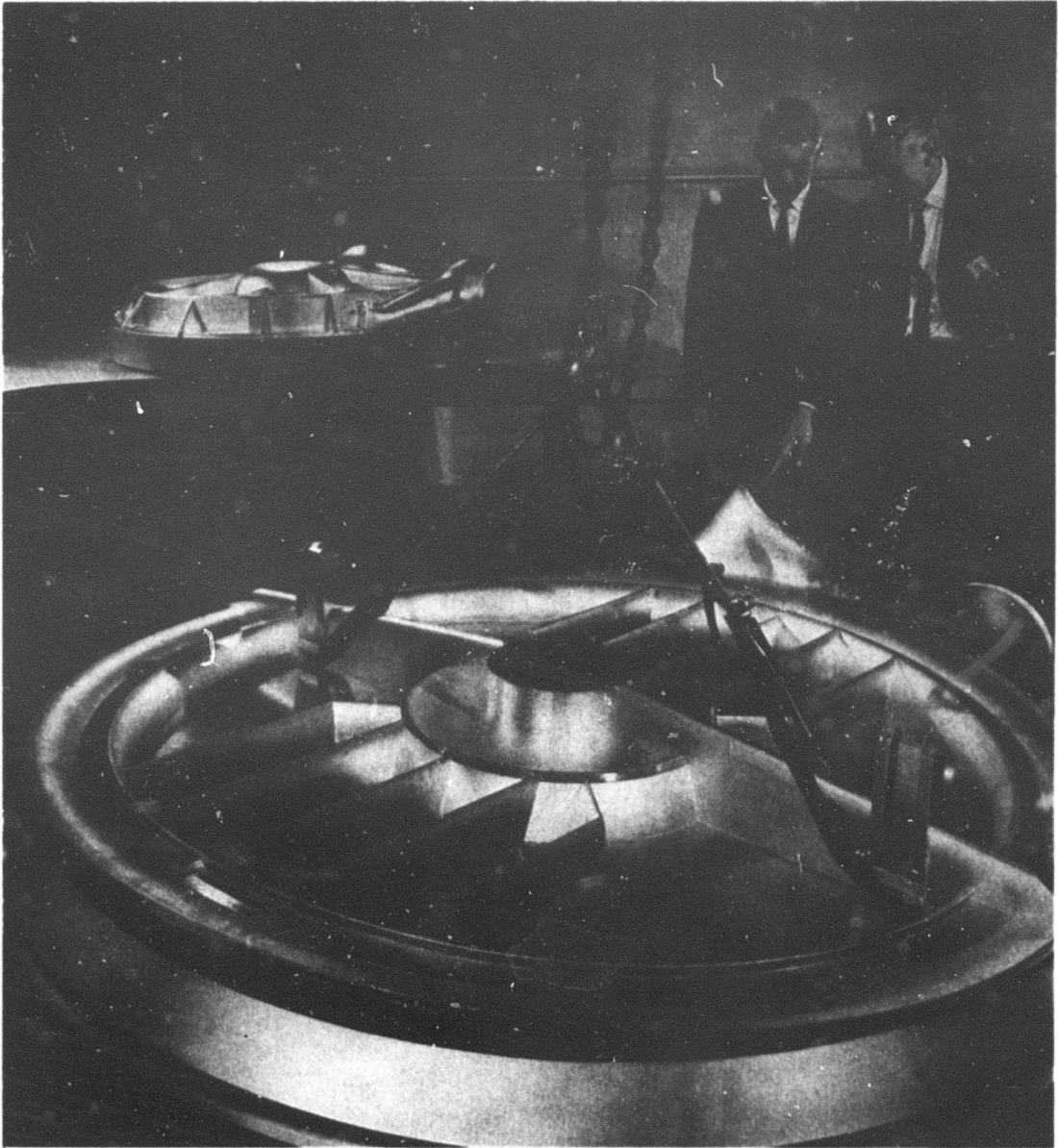


Figure 48. Main Lift Fan Mockup

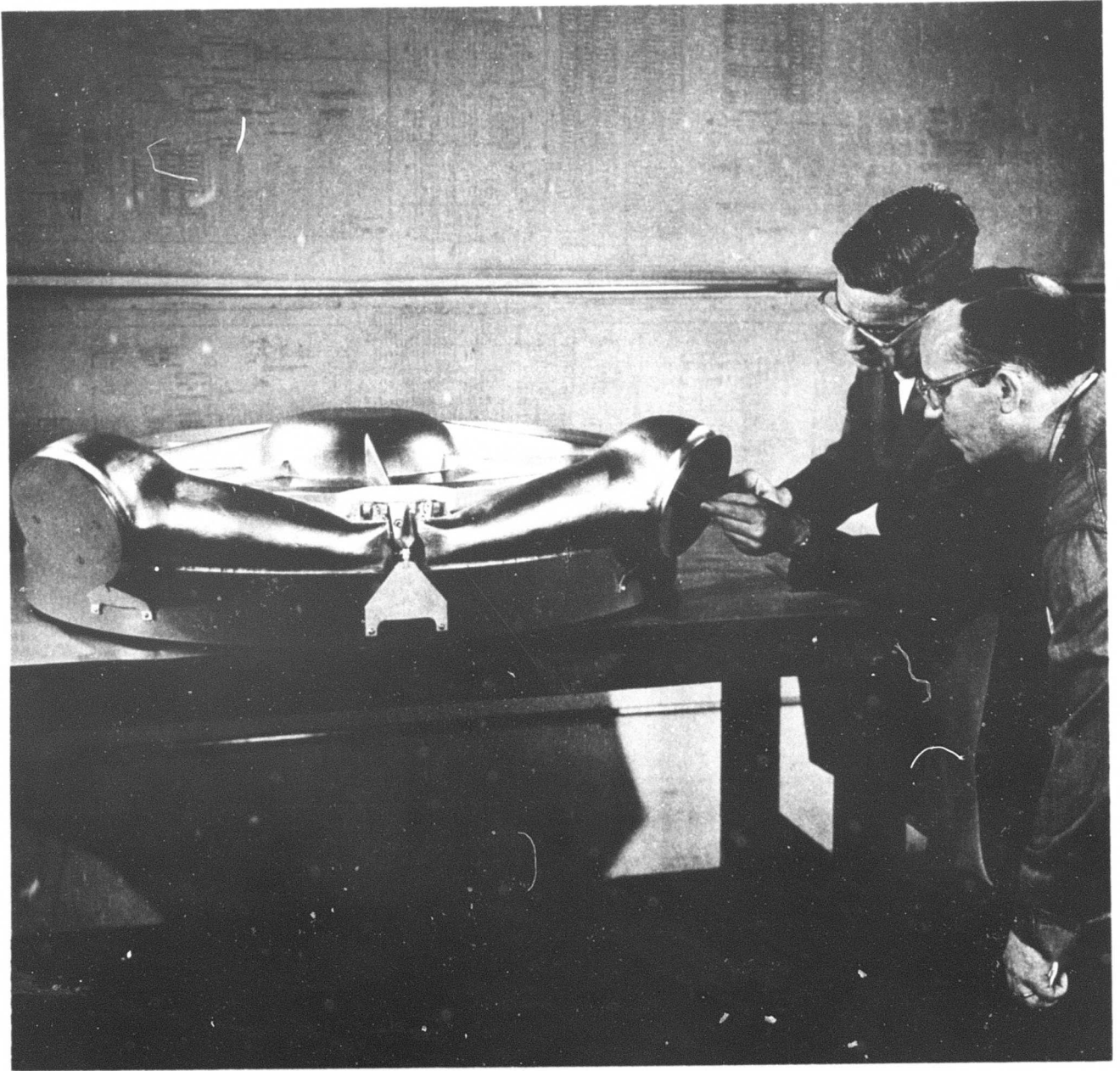


Figure 49. Pitch Fan Mockup



Figure 50. Diverter Valve Mockup